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IMPROVEMENT OF REAL TIME f_0F_2 PREDICTION FOR OTH RADARS

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29 August 1995

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13. ABSTRACT *(Maximum 200 words)*

Dandekar and Buchau (1986) presented an empirical algorithm for improving the f_oF_2 predictions for the sunrise transition period. The algorithm uses an average hourly gradient obtained from the previous four days' f_oF_2 observations and the 'present' f_oF_2, to predict f_oF_2 for the next hour. A further improvement was achieved by adding a second order correction term to the averaged slope. The second order correction takes into account 1) the change in 'now' f_oF_2 with respect to the previous four days' average f_oF_2 and 2) the increasing/decreasing gradient of f_oF_2. In the algorithm the sign of the second order term is selected so as to set a converging trend for the correction term. The algorithm is applied to a 24-hour period by dividing the time interval in two sections (04-16 and 16-04 LT) and reversing the sign of the second order correction for these two intervals, to assure the use of the converging trend from the algorithm for the 24 hour cycle. The scheme reduces the standard error in prediction from 0.9 MHz using the IONCAP method to 0.4 MHz at high solar activity and from 0.5 MHz using IONCAP to 0.3 MHz at low solar activity. The algorithm proposed here improves the f_oF_2 prediction by 50% at high solar activity and by 40% at low solar activity. The method provides a minimum of 25% improvement in the real time prediction of f_oF_2 for 80% of the time.

This level of reduction in the error of prediction of f_oF_2 is useful to the OTH radar frequency management, because every 6% change in 'M' (ratio of radar frequency to f_oF_2 at midpoint of the radar range) requires an adjustment of the radar operation frequency.

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Improvement of Real Time f_oF_2 Prediction for OTH Radars

1. INTRODUCTION

Dandekar and Buchau[1] (1986) proposed a technique for improving f_oF_2 predictions over an interval of 6 hours around the sunrise transition period. The technique uses the hourly average gradient from the previous four days' of f_oF_2 observations and the currently (present) observed f_oF_2 to predict f_oF_2 for the next hour. An additional improvement is achieved by adding a second order correction to the gradient by considering the sign of the change (positive/negative) of the present f_oF_2 with respect to the prior four days' average f_oF_2 for the same hour. In this report the same technique is tested for 24-hour real time prediction of f_oF_2. Thus, with a minor modification, the old scheme is found to be very promising.

For a simulation of the OTH East Coast radar situation three high latitude ionospheric stations in Canada: St. Johns (Newfoundland), Ottawa, and Winnipeg, are used. To cover different levels of solar activity, f_oF_2 data are selected for high (calendar year 1969) and low (calendar year 1976) solar activity. The use of the algorithm proposed herein improves the hourly prediction by 45 percent over the predictions obtained from using just the IONCAP model[2] (Lloyd et al, 1978).

The first section presents the algorithm and the analysis procedure used in the study. Section 2 discusses the distribution seen in the f_oF_2 data base, which forms the basis for the algorithm. Section 3 presents results using the algorithm. The last section summarizes the merits of the proposed scheme for improving f_oF_2 predictions.

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1.1 Algorithm for the Prediction of f_oF_2

The proposed algorithm is given by Eq. (1),

$$P(f_oF_{2_{n+1,i+1}}) = f_oF_{2_{n+1,i}} + \frac{1}{n}\sum_1^n (f_oF_{2_{n,i+1}} - f_oF_{2_{n,i}})\left(1 \pm \frac{f_oF_{2_{n+1,i}} - \overline{f_oF_{2_{n,i}}}}{\overline{f_oF_{2_{n,i}}}}\right) \ldots\ldots (1)$$

where the term on the left hand side of Eq. (1) is the predicted f_oF_2 for the n+1st day (today) for the next hour, 'i' is the 'present' hour, and n refers to the prior 'n' days. The first term on the right hand side (RHS) is the observed f_oF_2 today (n+1) for the present hour(i).

The second term (with the summation sign) is the averaged change in f_oF_2 between the i+1 and 'i'th hour from the prior n (n=4, used in this study) days. The term f_oF_2 (with overline) is the f_oF_2 averaged for n prior days for the 'i'th hour and is given by Eq. (2). Also, it can be used as the prediction for the present ('i'th) hour for (the n+1st day) today, if the 'present' f_oF_2 (the first term on the RHS) is not available. In Eq. (1) the last term in the end bracket is a second order correction to the slope where a positive or a negative sign is used, depending on the empirically determined time intervals.

Thus the prediction of f_oF_2 consists of the 'present' (observed) f_oF_2, plus the change in f_oF_2 over the next hour averaged for prior 'n' days, and with a correction term that modifies the slope of f_oF_2.

The estimate of today's $f_oF_{2\,n+1,i}$ can be obtained from the average of previous n days' f_oF_2 and is given by Eq. (2),

$$P(f_oF_{2_{n+1,i}}) \equiv \overline{f_oF_{2_{n,i}}} = \frac{1}{n}\sum_1^n f_oF_{2_{n,i}} \ldots\ldots (2)$$

In place of the observed, present (day n+1, 'i'th hour) f_oF_2, one can compute this first term on the RHS of Eq. (1), as the averaged f_oF_2 from Eq. (2). A similar form of weighted mean was proposed by Rush and Gibbs[3] for f_oF_2 predictions in 1973. In their scheme the prior day f_oF_2 was multiplied by a weight factor that decreased with the order of the day (prior day 1: factor n, prior day 2: factor n-1, prior day 3; factor n-3,.. up to 5 days). In our scheme (Eq. (1)) we compute a simple average of f_oF_2 without any such weight factors.

The proposed method is shown schematically in Figure 1 for a hypothetical set of data. The figure is divided into two sections. The left hand section (LHS) is for the period of increasing f_oF_2 and the right hand section (RHS) is for the period of decreasing f_oF_2. In these two sections of the figure, we see that for a given trend (increasing or decreasing f_oF_2) the change of (positive to negative) sign of the correction term in the last bracket on the RHS of Eq. (1) produces an opposite (converging or diverging) change. That is, f_oF_2 for the next hour deviates less (converges) or more (diverges) from the first order prediction. The comparison of the two periods shows that the same sign produces an opposite change in these trends. Also note that in Figure 1 on the last line of the algorithm, the numerator is a difference term. An interchange in the terms in the numerator interchanges the role of the positive and negative sign for this term. In the figure the lines closer to the central line show a converging trend and the lines farthest from it indicate a diverging trend. Thus we would like to know which trend, converging or diverging, produces better hourly predictions of f_oF_2, at a given time.

We propose (later in the discussion) the use of the scheme in the left hand side of Figure 1 for 04-16 LT and the right hand side of Figure 1 for 16-04 LT (converging trend in both cases) for predictions of f_oF_2.

1.2 Other Schemes

The IONCAP method is used as the baseline for determining the improvement achieved by any of these methods. Two schemes that truncate the RHS of Eq. (1) at different terms, and a correction term of opposite sign in the modified slope method, were also tested. The use of the equivalent of a perfect prediction from IONCAP allowed a test of how well a perfect prediction from IONCAP would serve an operational OTH radar. It was found that even a perfect prediction (of the monthly median f_oF_2 for each hour) from IONCAP does not improve the short term prediction of f_oF_2 very much.

In the analysis the mean monthly sunspot number (published by National Oceanic and Atmospheric Administration (NOAA), Boulder, Colorado, US) is used with IONCAP. In the OTH operation, Air Weather Service (AWS) computes the effective sunspot number from f_oF_2 observed from the network of 50 globally spaced ionosonde stations. The AWS scheme of the effective

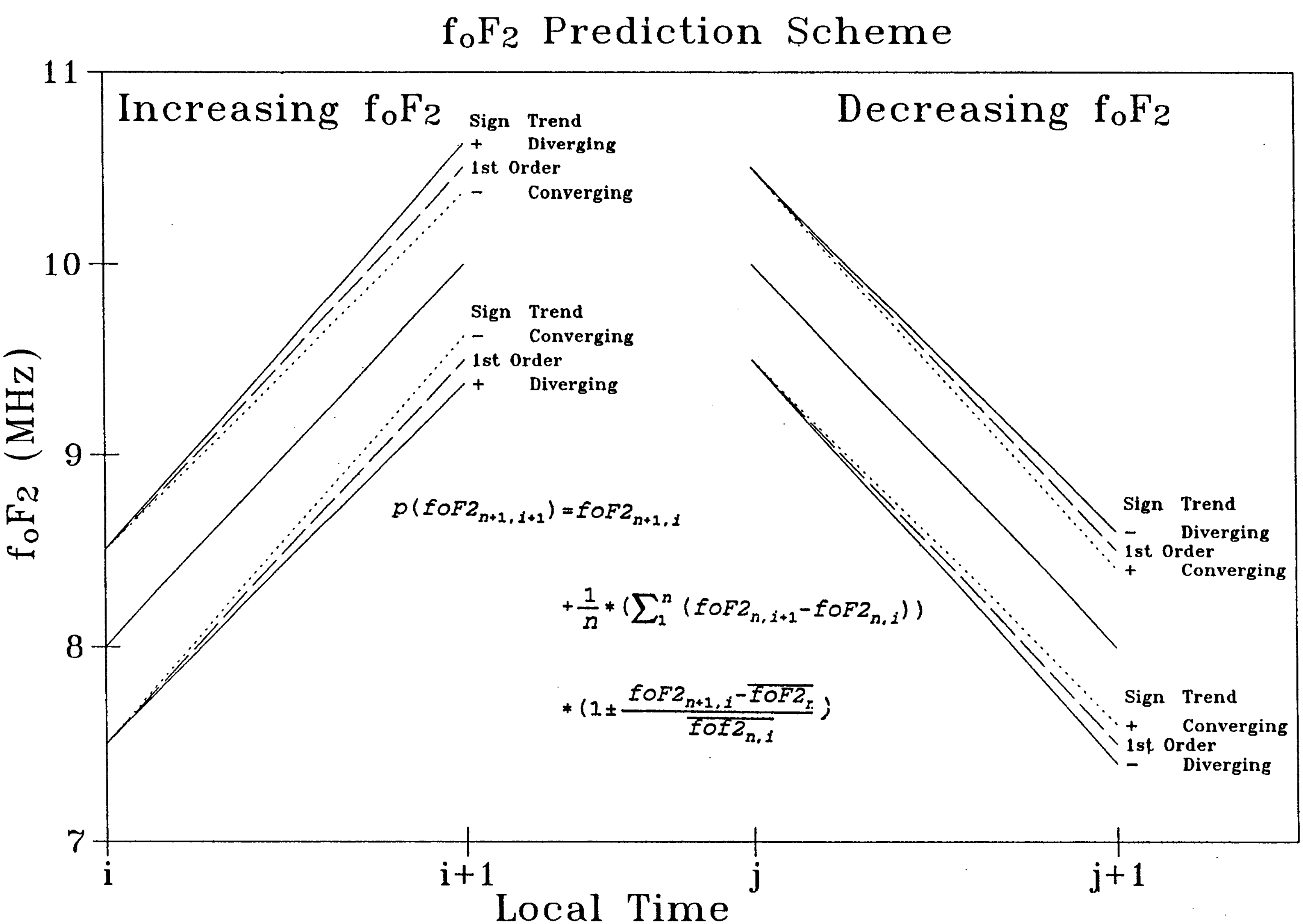

Figure 1. A scheme to predict f_oF_2 at hourly intervals using the present value of f_oF_2, the hourly slope of f_oF_2 and the slope correction. The left hand side (LHS) is for increasing f_oF_2 and the right hand side (RHS) for decreasing f_oF_2. Note the change in sign for increasing/decreasing trend for these sections.

sunspot number could not be used in this analysis. Note that as a starting point, the AWS uses the ITS-78 model (Barghausen et al[4] 1969), which is the precursor of the IONCAP model.

The monthly median predictions are computed for each hour from IONCAP using the observed mean sunspot number. These predictions are then used to determine the improvement in prediction achieved by the schemes described above. Thus we compare results from six methods:

1) IONCAP,

2) observed medians /accurate IONCAP,

3) prior four days' averaged f_oF_2 for the next hour,

4) the averaged slope method,

5) modified slope method using converging trend, and

6) modified slope method using diverging trend (depending on the sign used in the last bracket of Eq. (1)).

Three examples are presented to demonstrate the improvement of the predictions by use of the algorithm. Figure 2 shows a mass plot of f_oF_2 data from Argentia, Canada for November 1990 along with the observed median values and the IONCAP predictions (SSN=140). Note that the observed medians nicely follow the IONCAP predictions, but the IONCAP predictions on the average are 1 MHz greater than the median values. Also, the median/IONCAP provides a single value for f_oF_2 for each hour of a given month, whereas the observations cover a wide range of 2.5 MHz at 09 UT, to 14.2 MHz at 17 UT. Note that the observations for Julian day 90-331 (November 27,1990, with a major magnetic storm) show a large difference from the remaining data. Figure 3 shows the predictions for Argentia from the full algorithm of Eq. (1) along with the observations for three days selected from Figure 2. Figure 3 shows that the predictions from the algorithm are close to the actual observations and show an improvement in the prediction over both the observed median and IONCAP predictions. Considering the large deviation of the frequency for 10-24 UT on Julian day 331 the predictions from the algorithm are very good. This demonstrated success of the algorithm must be validated with a larger data base.

Before applying the algorithm to a larger database, the systematic behavior of the f_oF_2 observations is examined. This systematic behavior allows the use of the proposed algorithm for a significant reduction in the prediction error.

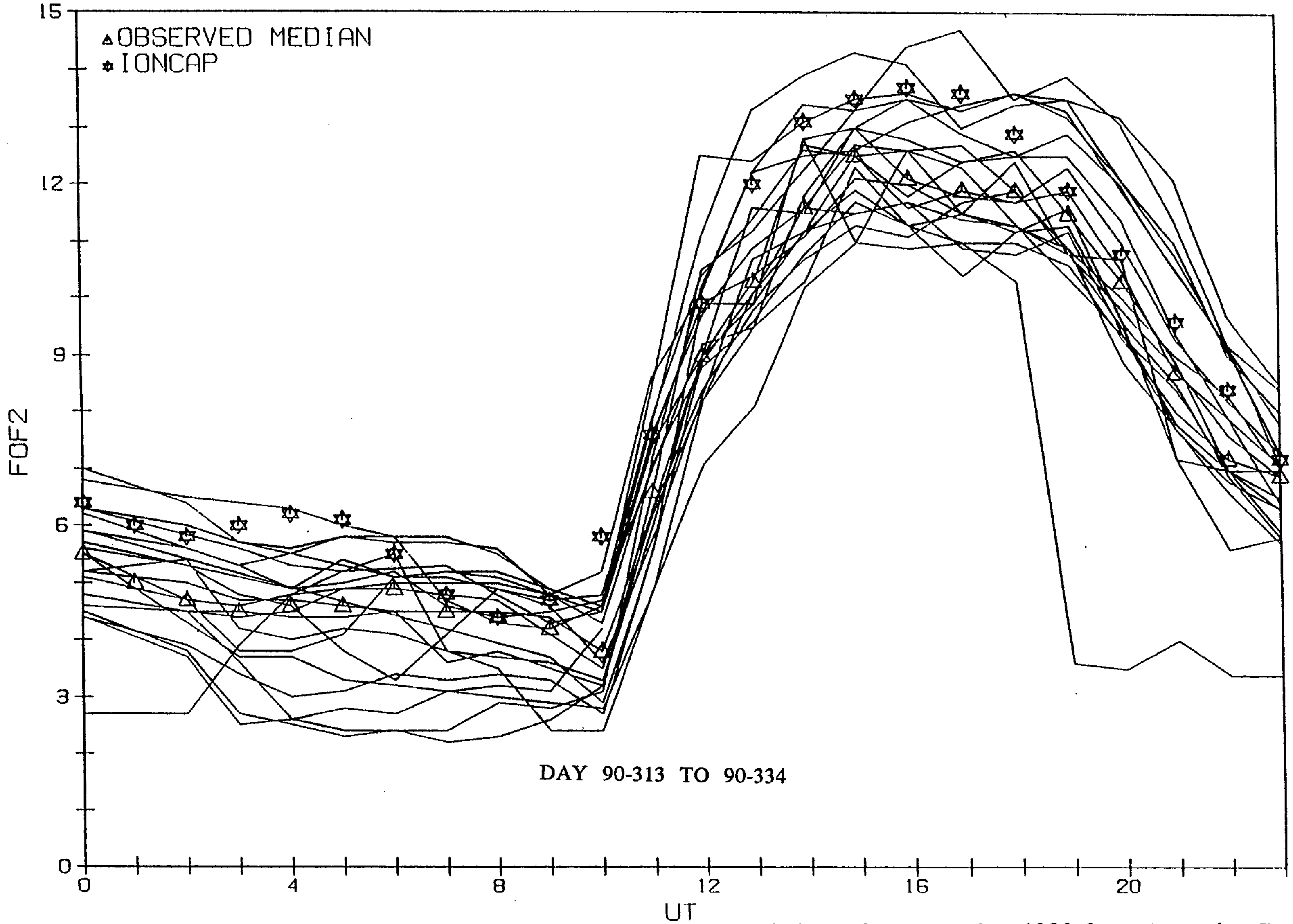

Figure 2. Mass plot of observed f_oF_2, observed median and IONCAP predictions for November 1990 from Argentia, Canada.

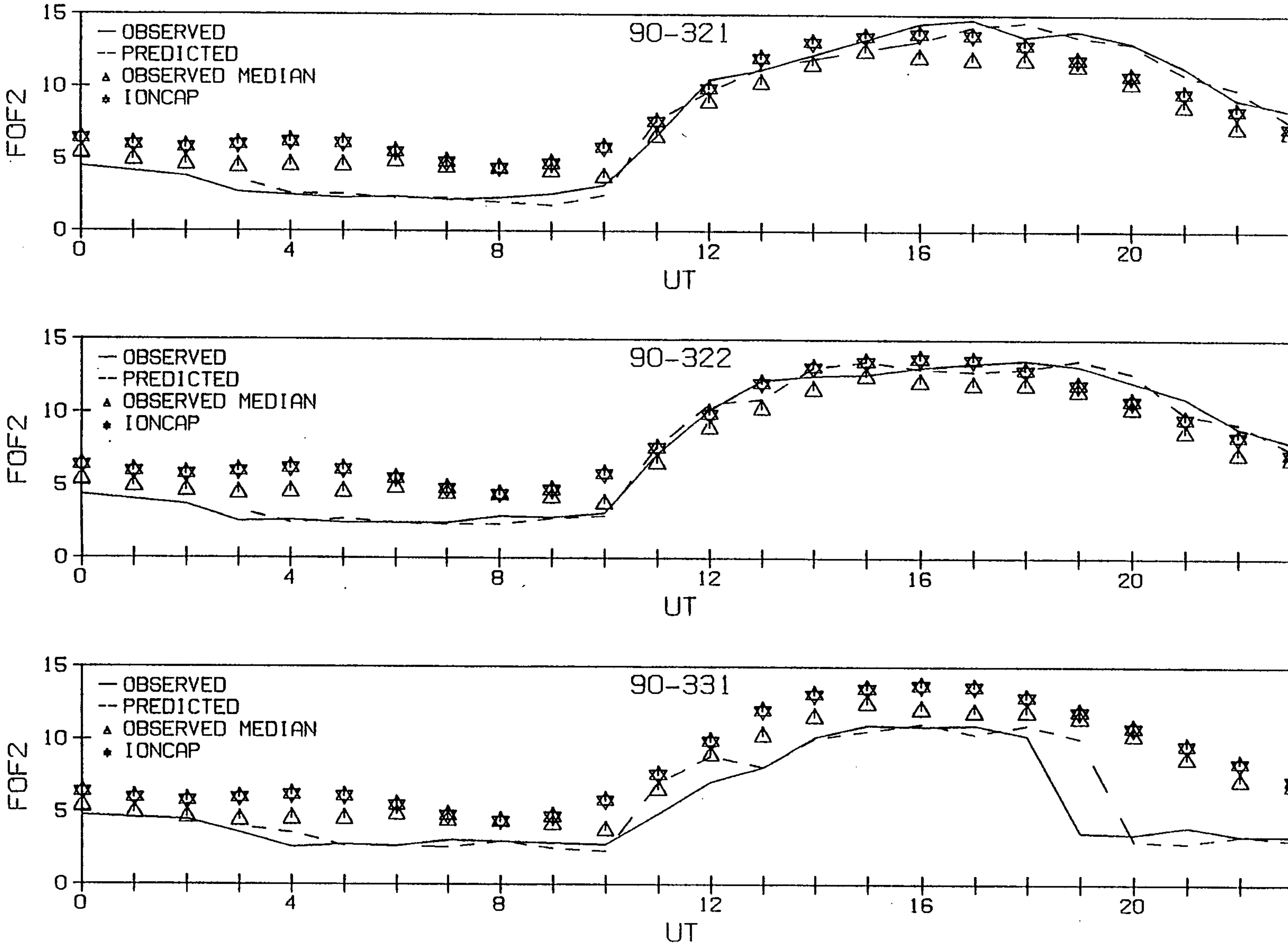

Figure 3. Comparison of observations with predictions from the proposed algorithm.

2. DATA BASE

The ionospheric stations representing the northern sector of the OTH East Coast Radar are listed in Table 1. The selection of the stations is very much dependent on the availability of a reasonably continuous set of observations of f_oF_2 over a long time period. The table lists the name, geographic, and corrected geomagnetic (CG) coordinates of the stations. St. Johns, Canada is in the northern sector of the OTH ECRS coverage. Most often this station is south of the midlatitude F-layer trough. Although the second station, Ottawa, Canada, does not lie in the OTH coverage, its geographic latitude is a good representation of the OTH coverage area. The third station, Winnipeg, Canada, is both geographically and geomagnetically north of both Ottawa and St. Johns, and is close to the auroral oval. The ionospheric characteristics of Winnipeg are close to those of Goose Bay, Canada. Goose Bay lies in the northern sector of the ECRS. Because Goose Bay did not operate prior to 1972 it could not be used in this study to cover a full solar cycle.

Table 1. Ionospheric Stations Used in the Study

	Geographic		Corr. Geomagnetic	
Station	Lat. N	Long. E	Lat. N	Long. E
St. Johns	47.6	307.3	57.6	29.1
Ottawa	45.1	283.8	58.5	355.7
Winnipeg	49.8	265.6	61.1	323.5

For the selected stations, the f_oF_2 data for the calendar years 1969 and 1976 are used as representative of the high and low phases of solar activity. The observed averaged monthly sunspot numbers (SSN) for the years of high and low solar activity are 106 and 11 respectively. Examination of the diurnal behavior of f_oF_2 shows why the proposed algorithm provides good f_oF_2 predictions. This is shown in Figures 4A-E for 1969 (no continuous data are available for Winnipeg) and 1976. Each figure is divided into 12 blocks. Each block presents the month (noted in the upper corner of the block). For each month there are three curves showing the upper quartile, the median, and the lower quartile. Gaps in the data are shown by dotted lines. The points to note are: a) the diurnal variation of f_oF_2 shows a maximum around 1500 LT and a minimum in the predawn hours,

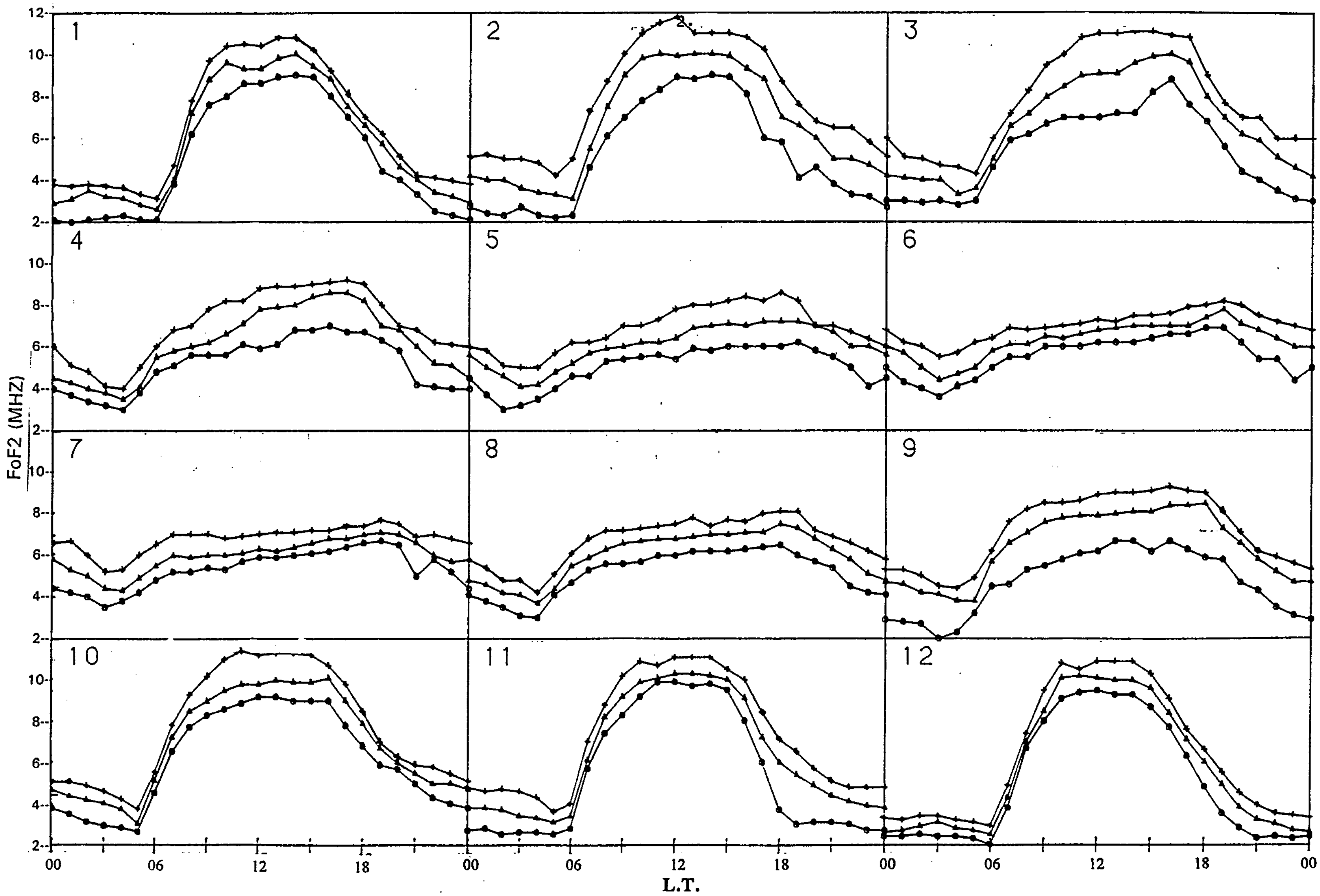

Figure 4A. Diurnal variation of f_oF_2 at St. Johns in 1969.

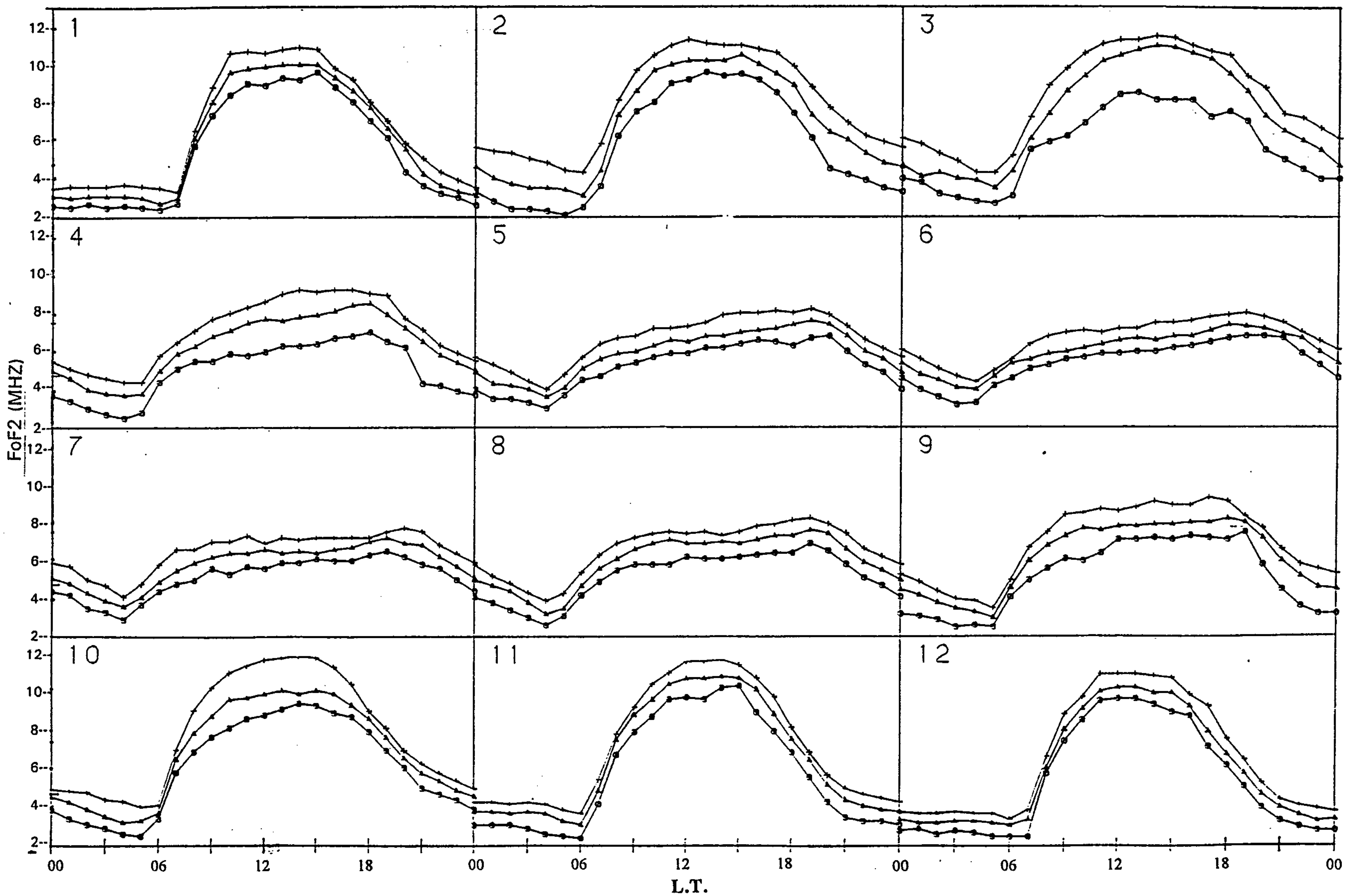

Figure 4B. Diurnal variation of f_oF_2 at Ottawa in 1969.

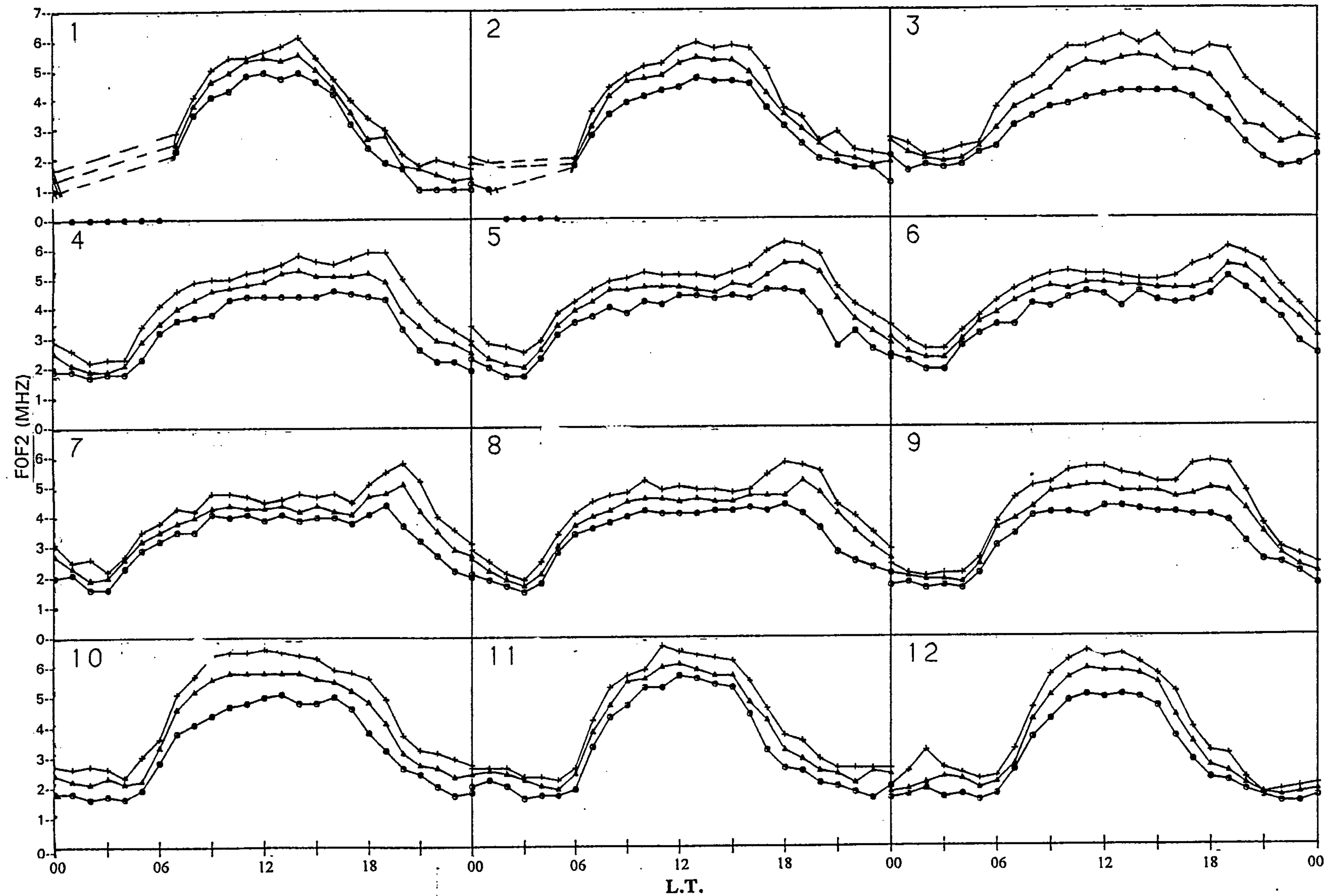

Figure 4C. Diurnal variation of f_oF_2 at St. Johns in 1976.

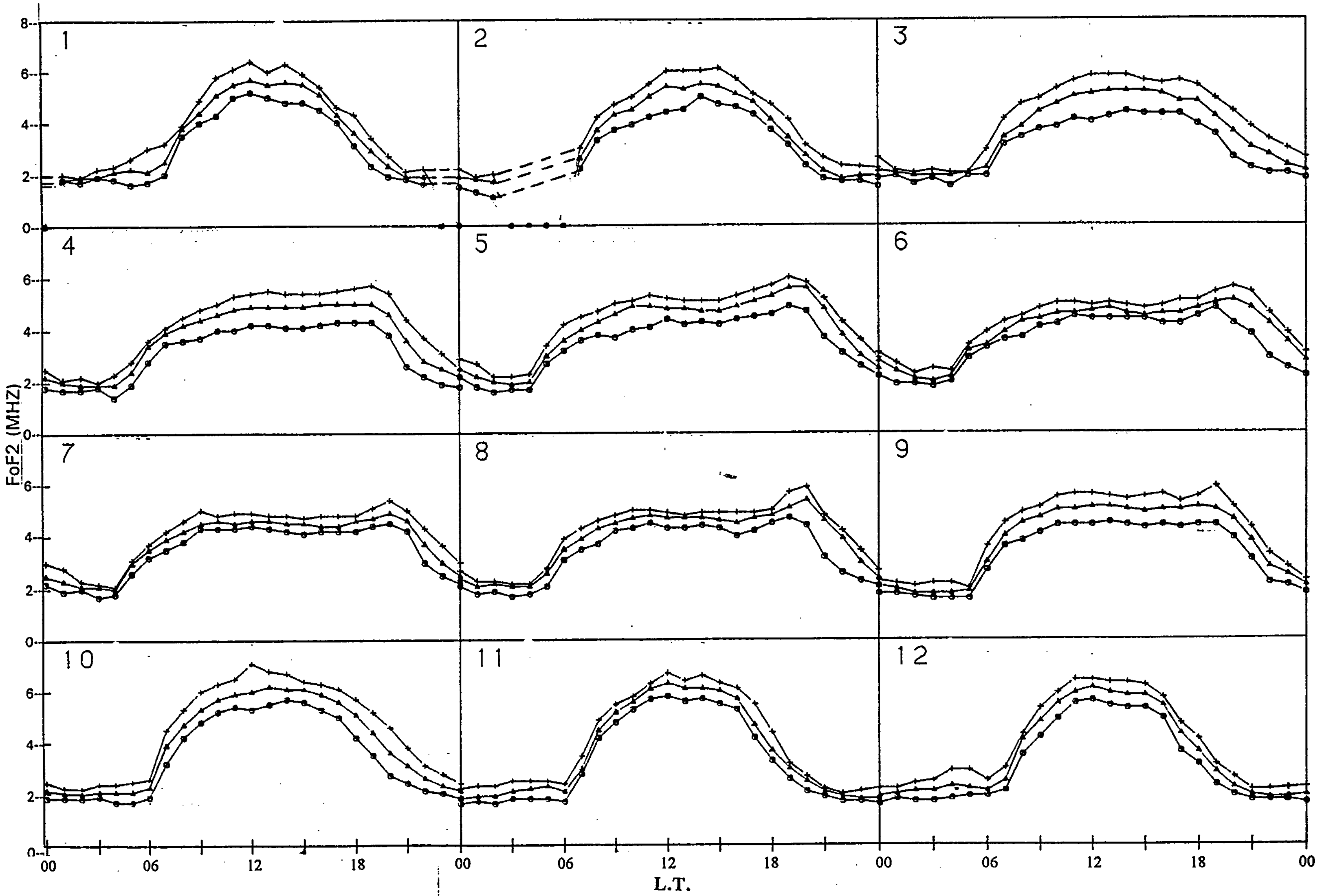

Figure 4D. Diurnal variation of f_oF_2 at Ottawa in 1976.

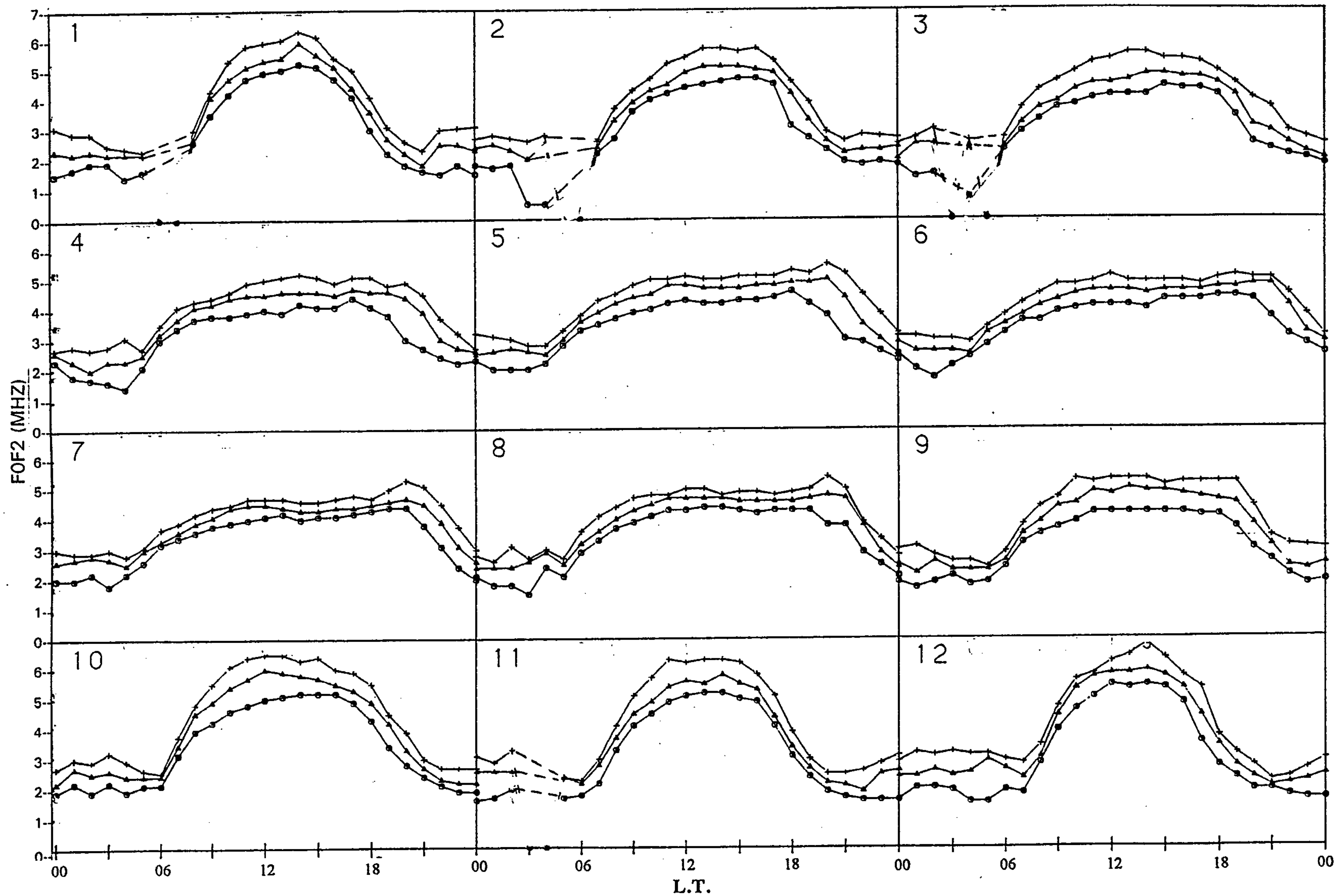

Figure 4E. Diurnal variation of f_oF_2 at Winnipeg in 1976.

b) between the maximum and the minimum the diurnal variation changes by a factor of 2, c) the diurnal variation is largest in winter months (October to March) as shown in rows 1 and 4 and relatively smaller in summer months (April to September) as shown in rows 2 and 3, and d) the peak f_oF_2 decreases by a factor of 2 between the high (1969) and low (1976) solar activity periods. This systematic diurnal variation is the reason that good predictions using the algorithm in Eq. (1) are possible.

The percent change (slope) in hourly f_oF_2 is computed from Eq. (3)

$$P_i = 100 \frac{f_oF_{2_{i+1}} - f_oF_{2_i}}{(f_oF_{2_{i+1}} + f_oF_{2_i})/2} \quad \ldots\ldots (3)$$

The median hourly slopes in f_oF_2 are shown in Figures 5A-E. Each figure presents the contours of median hourly slopes for the whole year for each month for all 24 hours. The positive sign refers to an increase in f_oF_2 and the negative sign refers to a decrease in f_oF_2. There are two periods of large changes (≥20 percent), one around the sunrise and the other around the sunset. The sharpest increase in f_oF_2 is seen between 04-08 LT. The sunrise changes are the largest (≥40 percent) in the winter months.

The other factor to consider is the spread of f_oF_2 for a given LT hour. For each hour of a given month the normalized spread (δf_oF_2) is computed from the equation

$$\delta f_oF_2 = 100 \frac{f_oF_{2_{+\sigma}} - f_oF_{2_{-\sigma}}}{2 f_oF_{2_{Med}}} \quad \ldots\ldots (4)$$

The terms in Eq. (4) are median f_oF_2 (not mean f_oF_2), and f_oF_2 $\pm\sigma$ levels. If the f_oF_2 distribution is normal, the median and mean f_oF_2 are equal. Also, the magnitudes of $\pm\sigma$ levels will be the same. In this analysis the median (50th percentile) and $\pm\sigma$ (84th and 16th percentiles, that is, 68 percent population around the median) levels were determined from the observed distribution of f_oF_2.

The time dependence of (relative) spread in f_oF_2 is shown in Figures 6A-E. Figures 6A-E have the same format as Figures 4A-E. These figures show that the spread of f_oF_2 is smaller for the

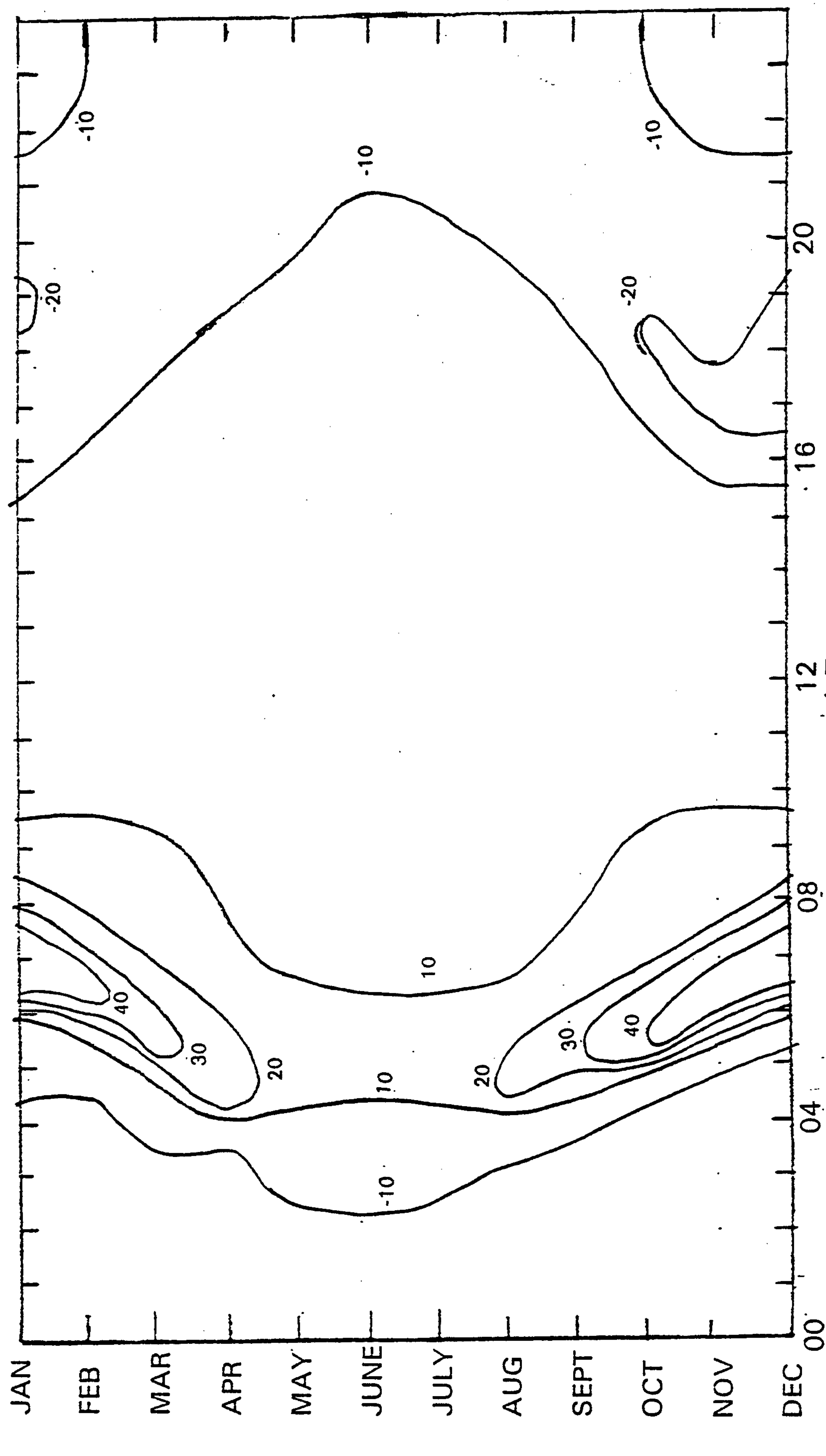

Figure 5A Median monthly variation(%) in f_oF_2 at St. Johns in 1969.

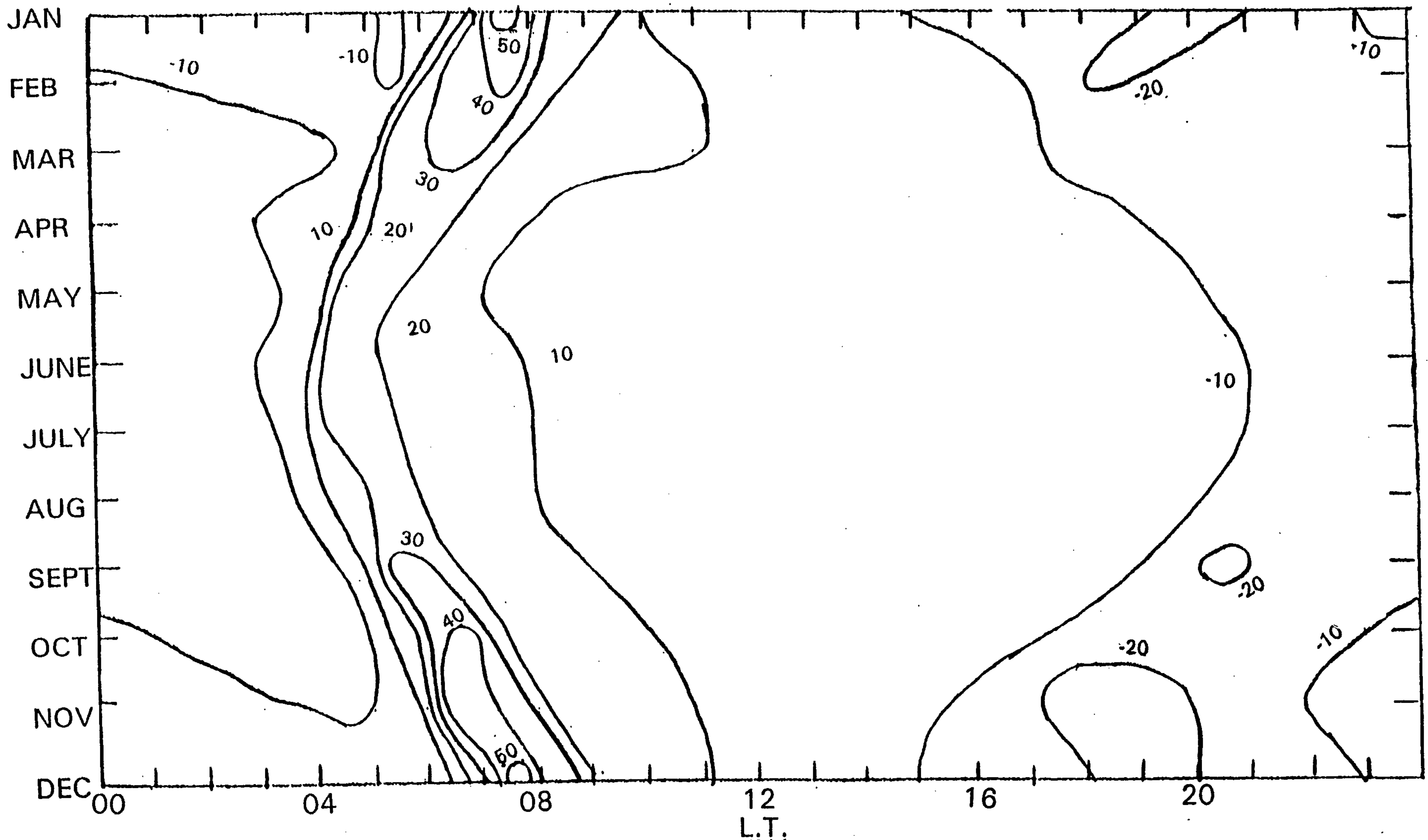

Figure 5B Median monthly variation(%) in f_oF_2 at Ottawa in 1969.

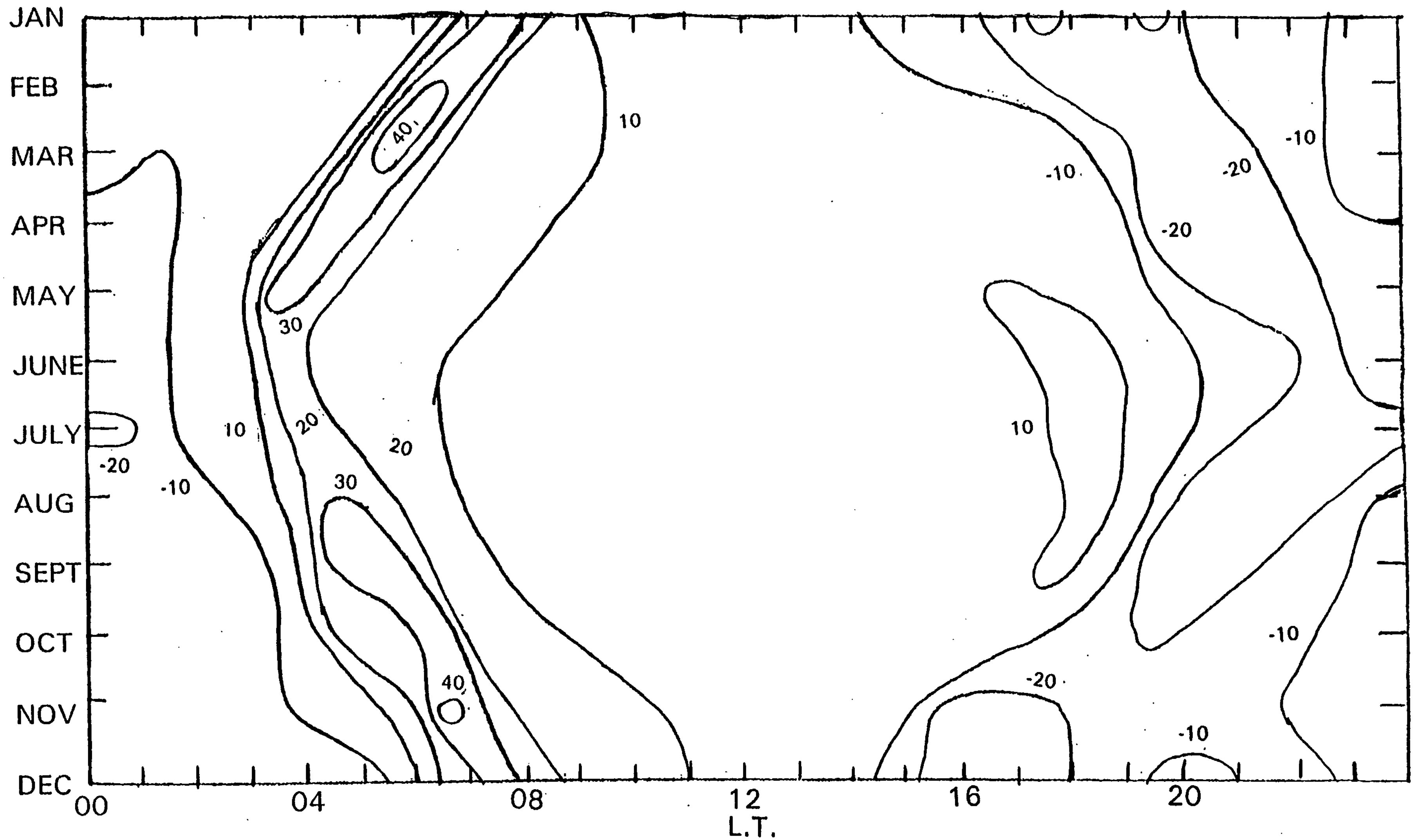

Figure 5C Median monthly variation(%) in f_oF_2 at St. Johns in 1976.

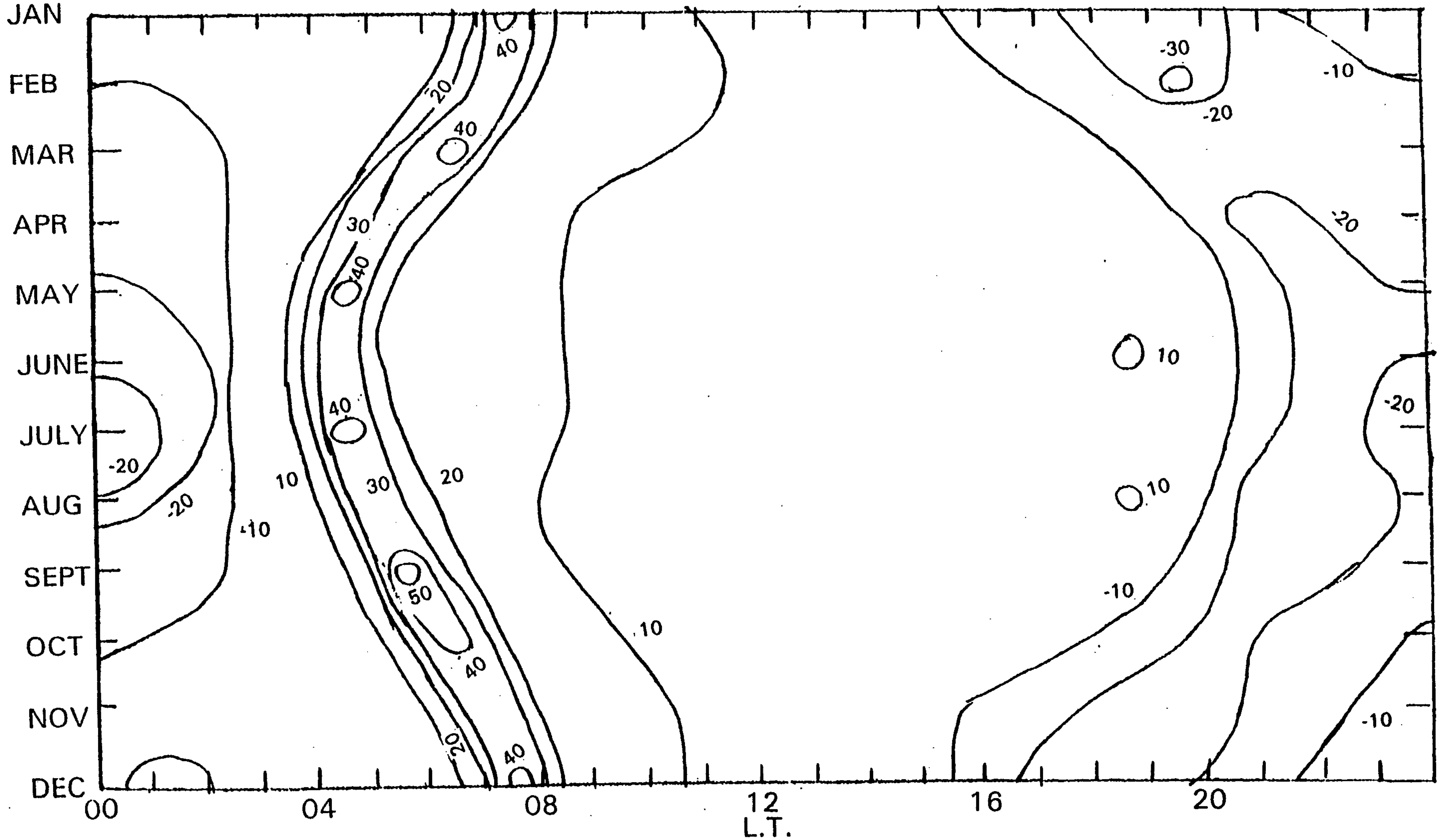

Figure 5D Median monthly variation(%) in f_oF_2 at Ottawa in 1976.

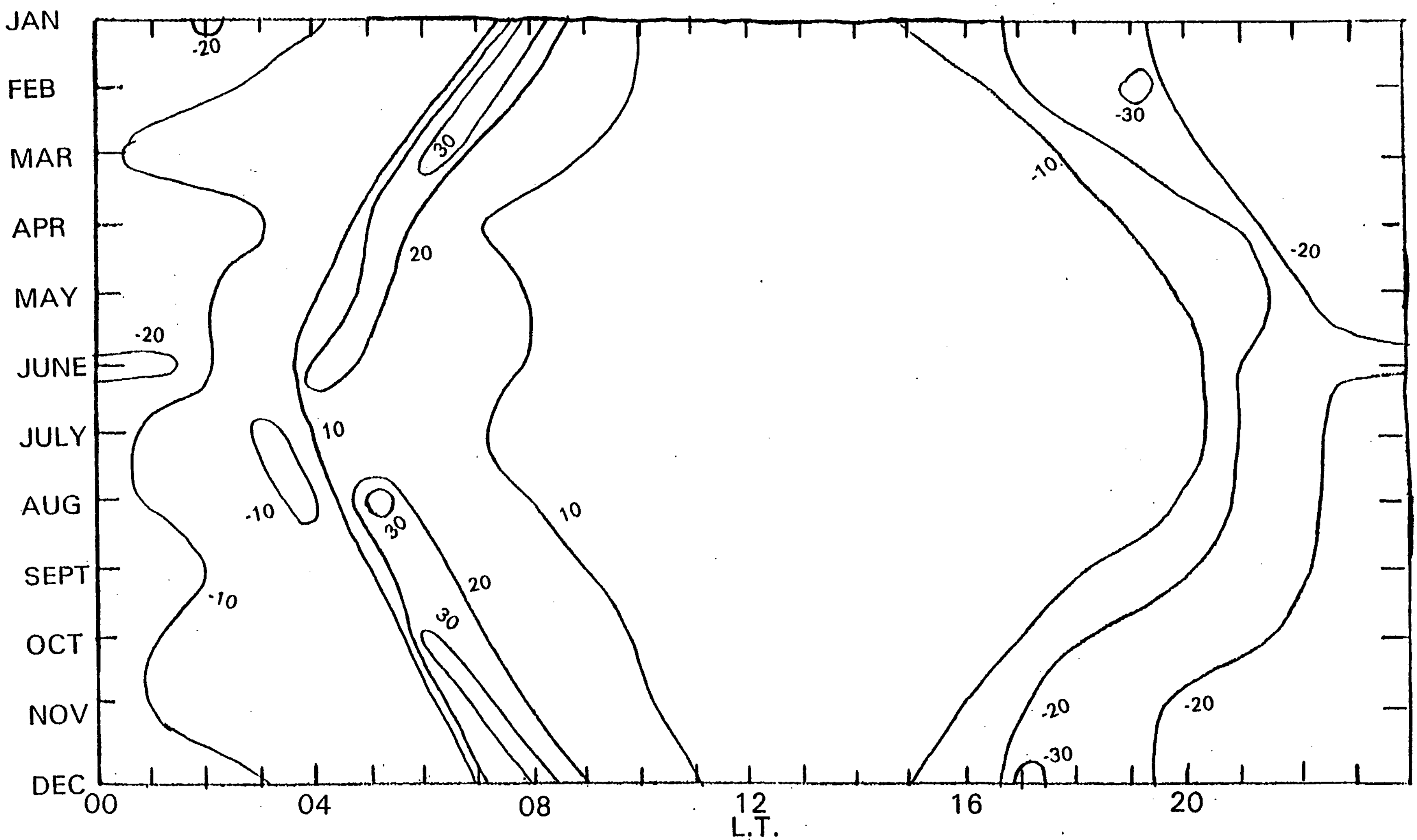

Figure 5E Median monthly variation(%) in f_oF_2 at Winnipeg in 1976.

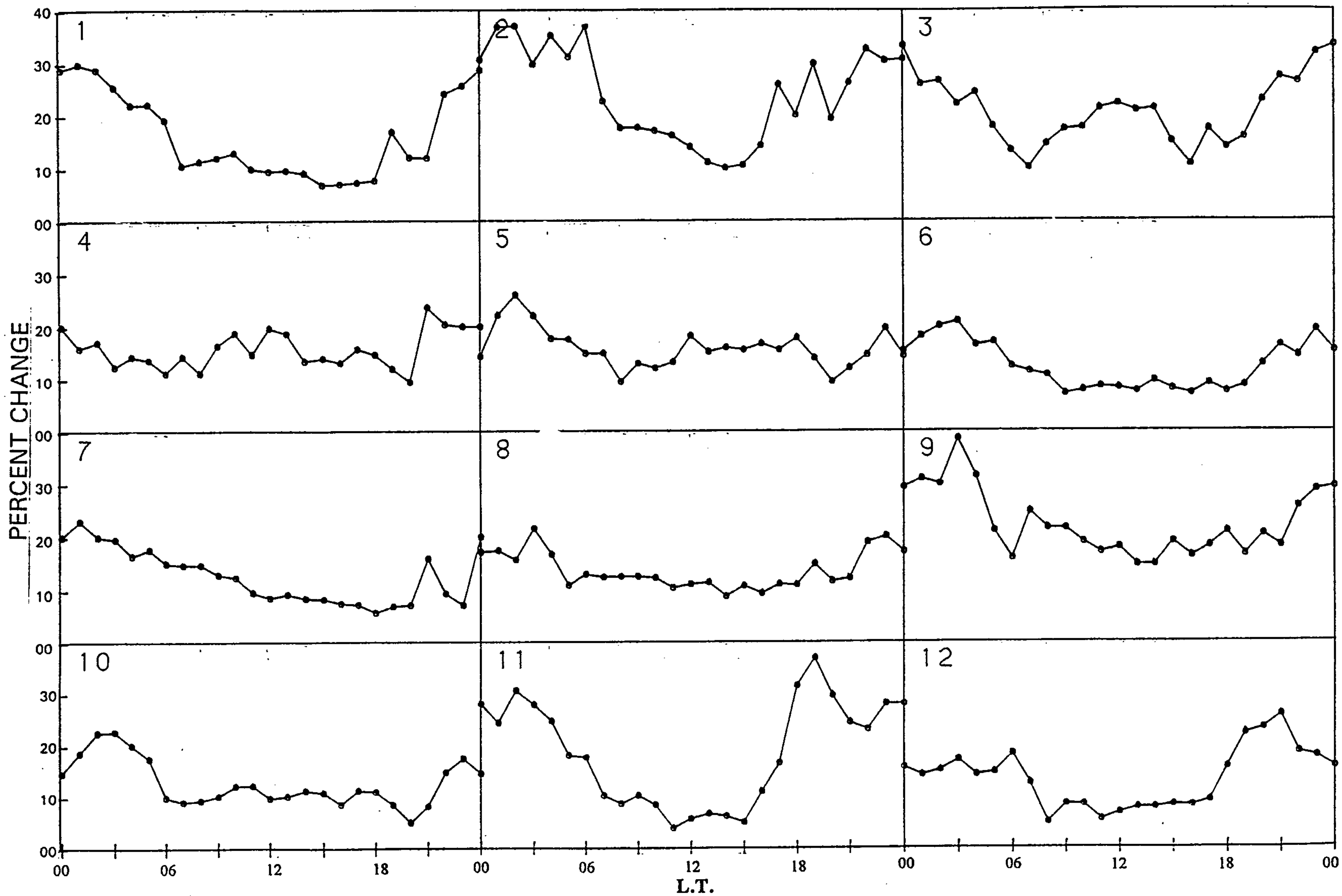

Figure 6A. Percent variation between $\pm\sigma$ levels of f_oF_2 at St. Johns in 1969.

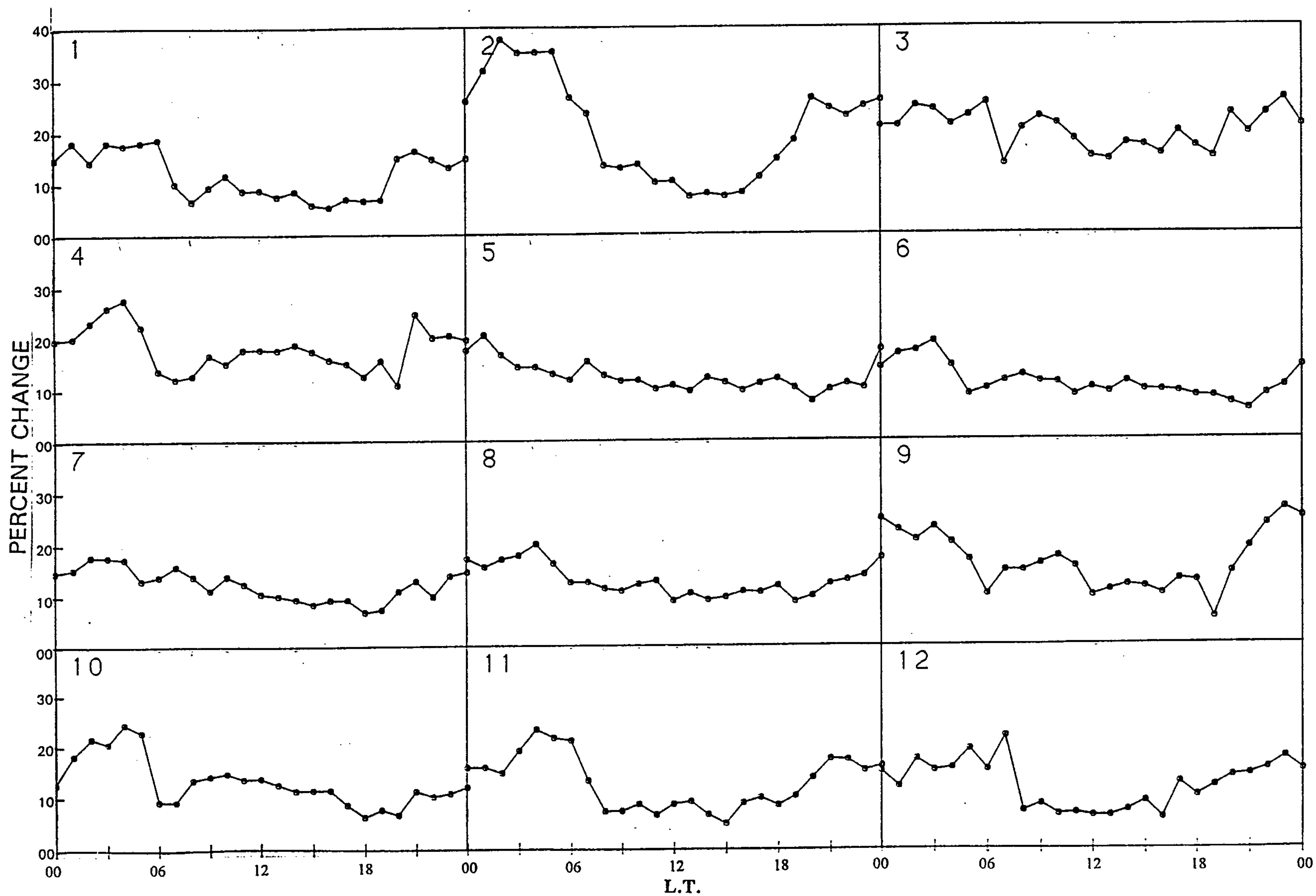

Figure 6B. Percent variation between $\pm\sigma$ levels of f_oF_2 at Ottawa in 1969.

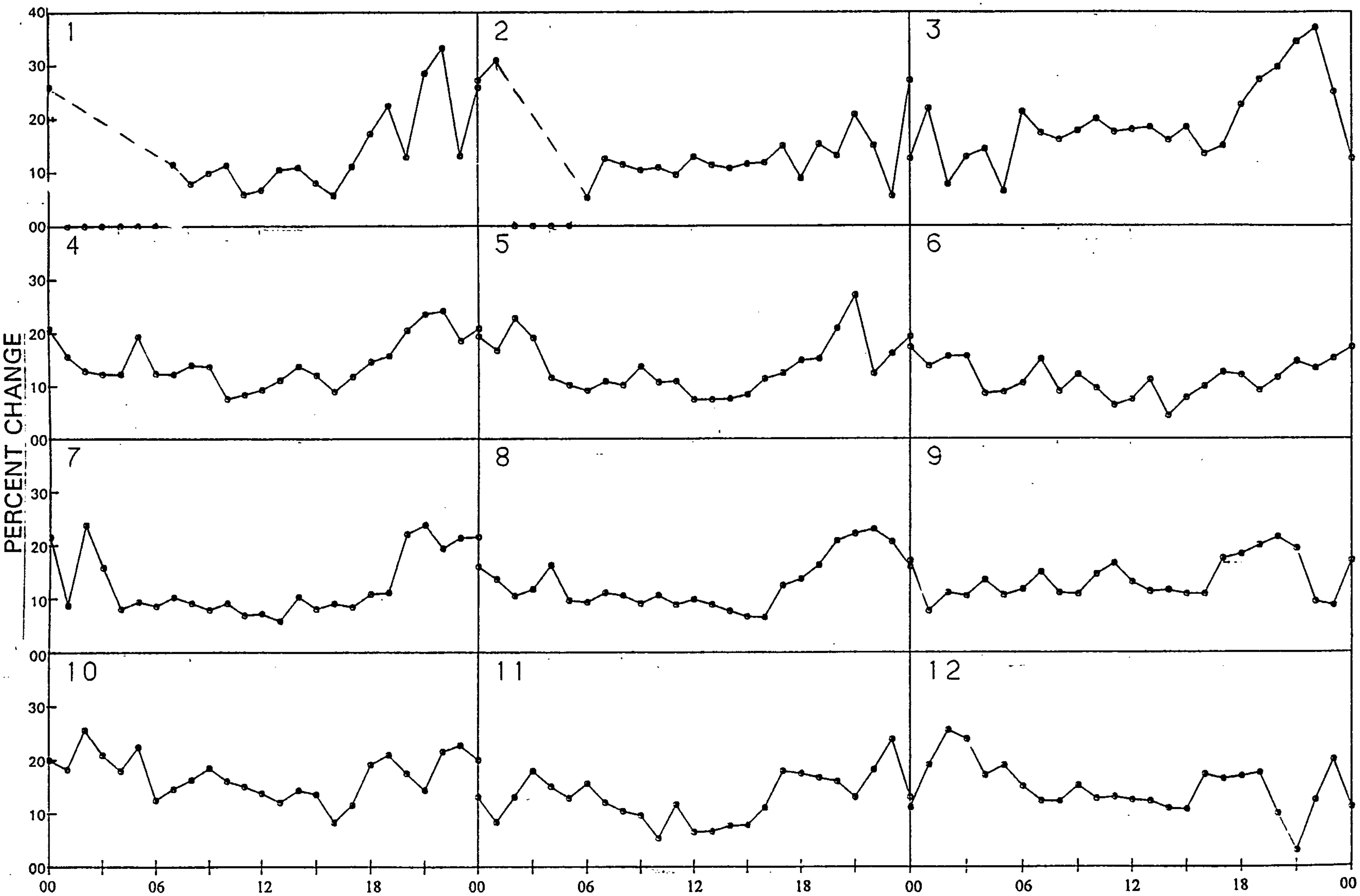

Figure 6C. Percent variation between $\pm\sigma$ levels of f_oF_2 at St. Johns in 1976.

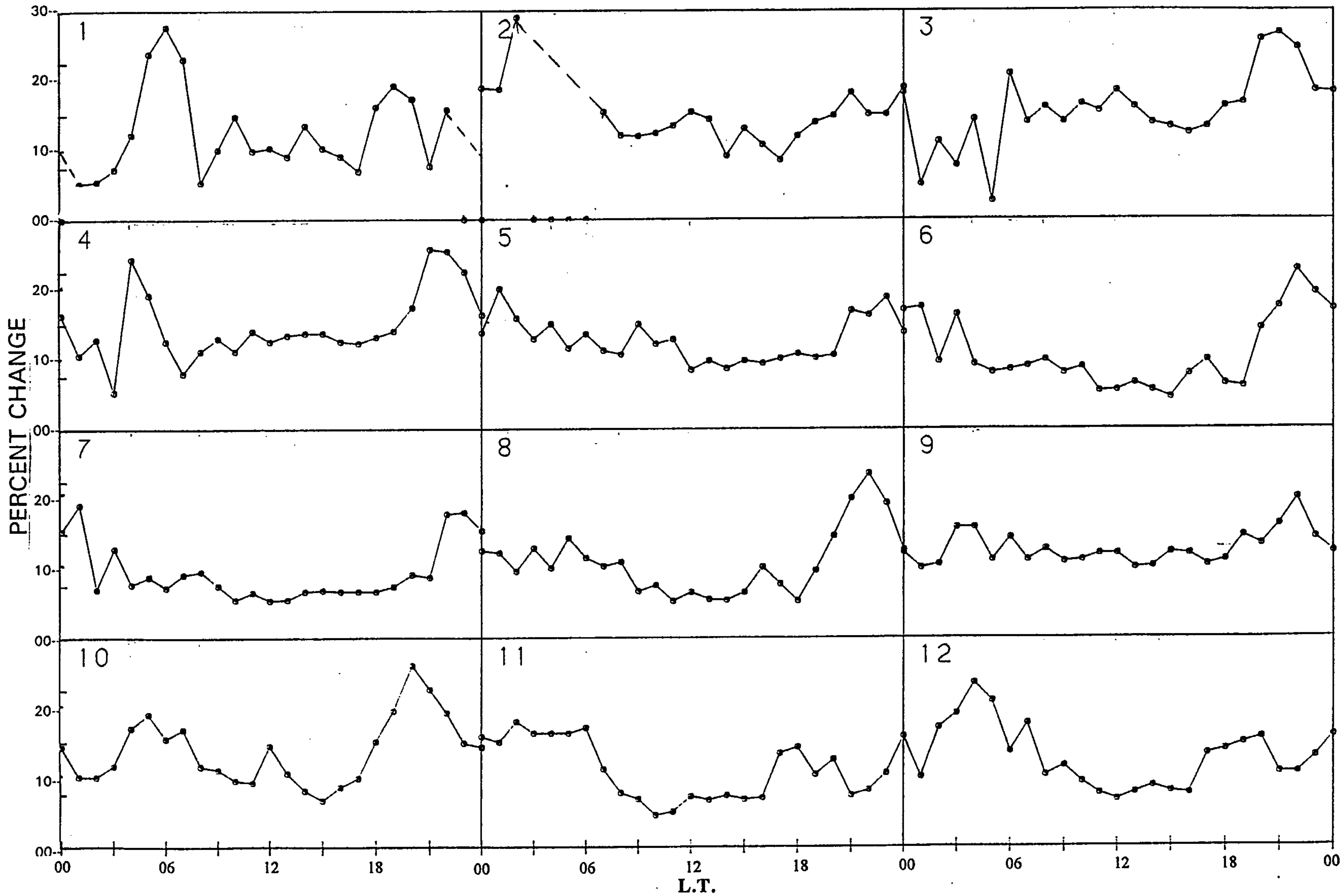

Figure 6D. Percent variation between ±σ levels of f_oF_2 at Ottawa 1976.

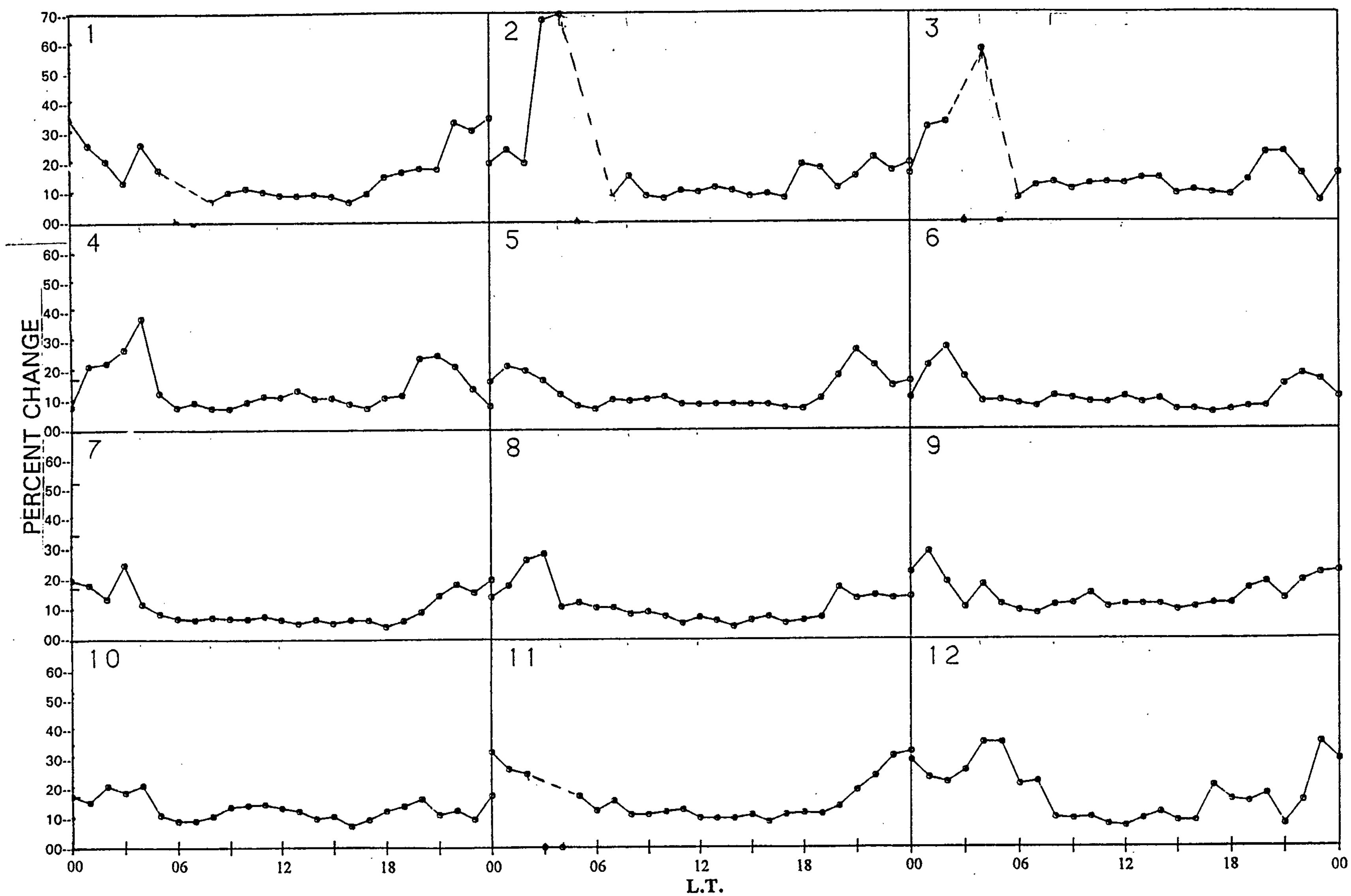

Figure 6E. Percent variation between ±σ levels of f_oF_2 at Winnipeg in 1976.

daytime hours and larger for nighttime and for the transition periods of sunrise and sunset. We find that the success of the f_oF_2 prediction algorithm is inversely related to this spread; that is, smaller the spread, better is the prediction of f_oF_2. Note that we are considering the relative spread in f_oF_2 (not the absolute values of the spread). In the following, the algorithm is used to compute the predicted f_oF_2 by all the six methods mentioned above.

3. ANALYSIS

The predictions from the IONCAP program are used as the reference for determining the improvement in the prediction of f_oF_2 by the algorithm (Eq. (1)). Therefore, the first step is to determine the error between the observed f_oF_2 and the f_oF_2 predicted by the IONCAP program. The monthly averaged sunspot number listed in Table 2 is used as an input to the IONCAP program.

Table 2. Zurich Sunspot Number

YEAR	1969	1976
MONTH		
JANUARY	104	8
FEBRUARY	121	4
MARCH	136	22
APRIL	107	19
MAY	120	12
JUNE	106	12
JULY	97	2
AUGUST	98	16
SEPTEMBER	91	14
OCTOBER	96	21
NOVEMBER	94	5
DECEMBER	98	15
AVERAGE	106	11

The comparison of the observed monthly median f_oF_2 with monthly median prediction of f_oF_2 from the IONCAP is shown in Figures 7A-E as a function of time of the day and season. These figures show that at high solar activity (year 1969) the range of f_oF_2 is 3 to 11 MHz, and the standard error between the prediction and observation is less than 1 MHz. At low sunspot activity (year 1976) the

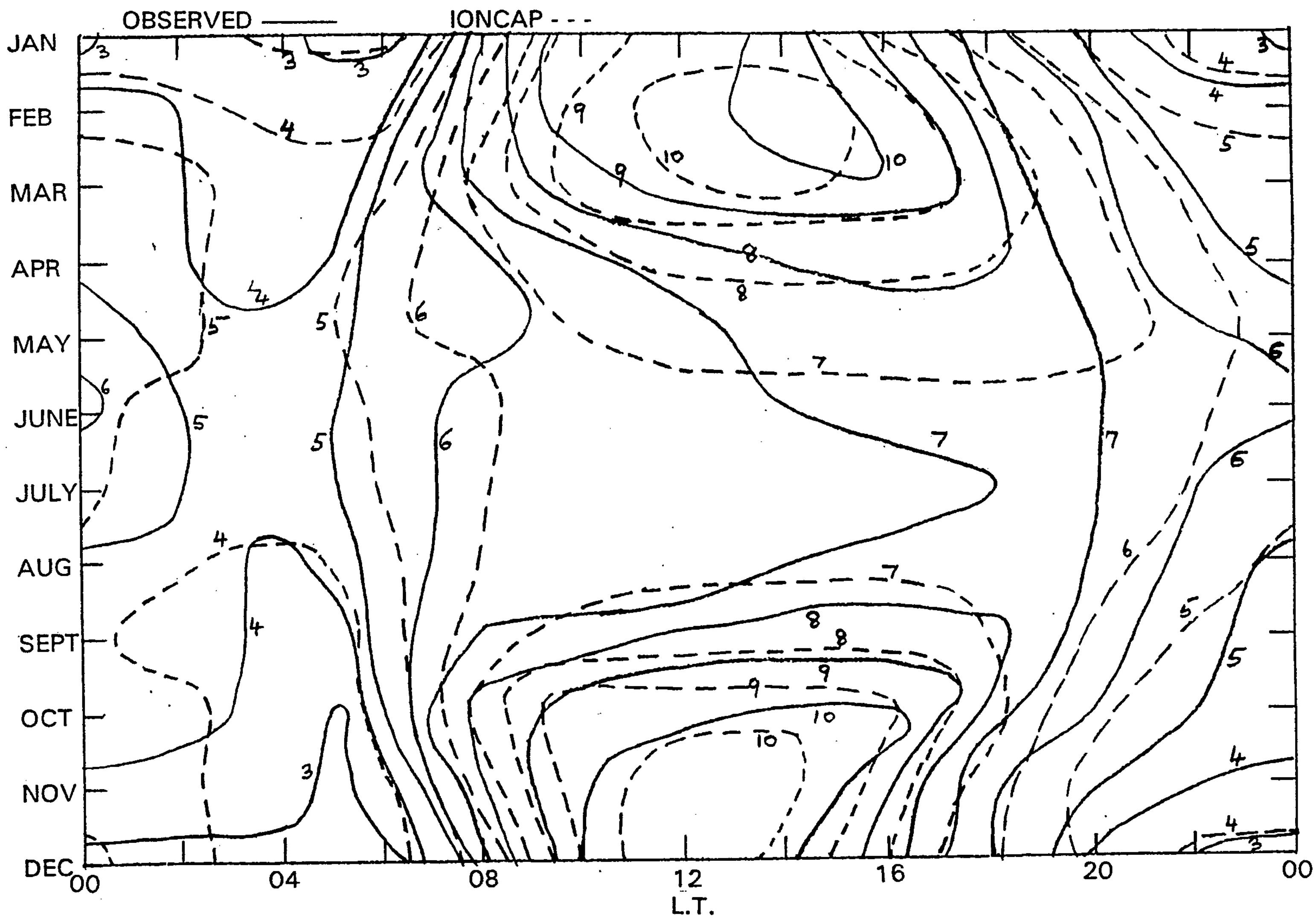

Figure 7A Monthly median contours of f_oF_2 at high solar activity (1969) at St. Johns.

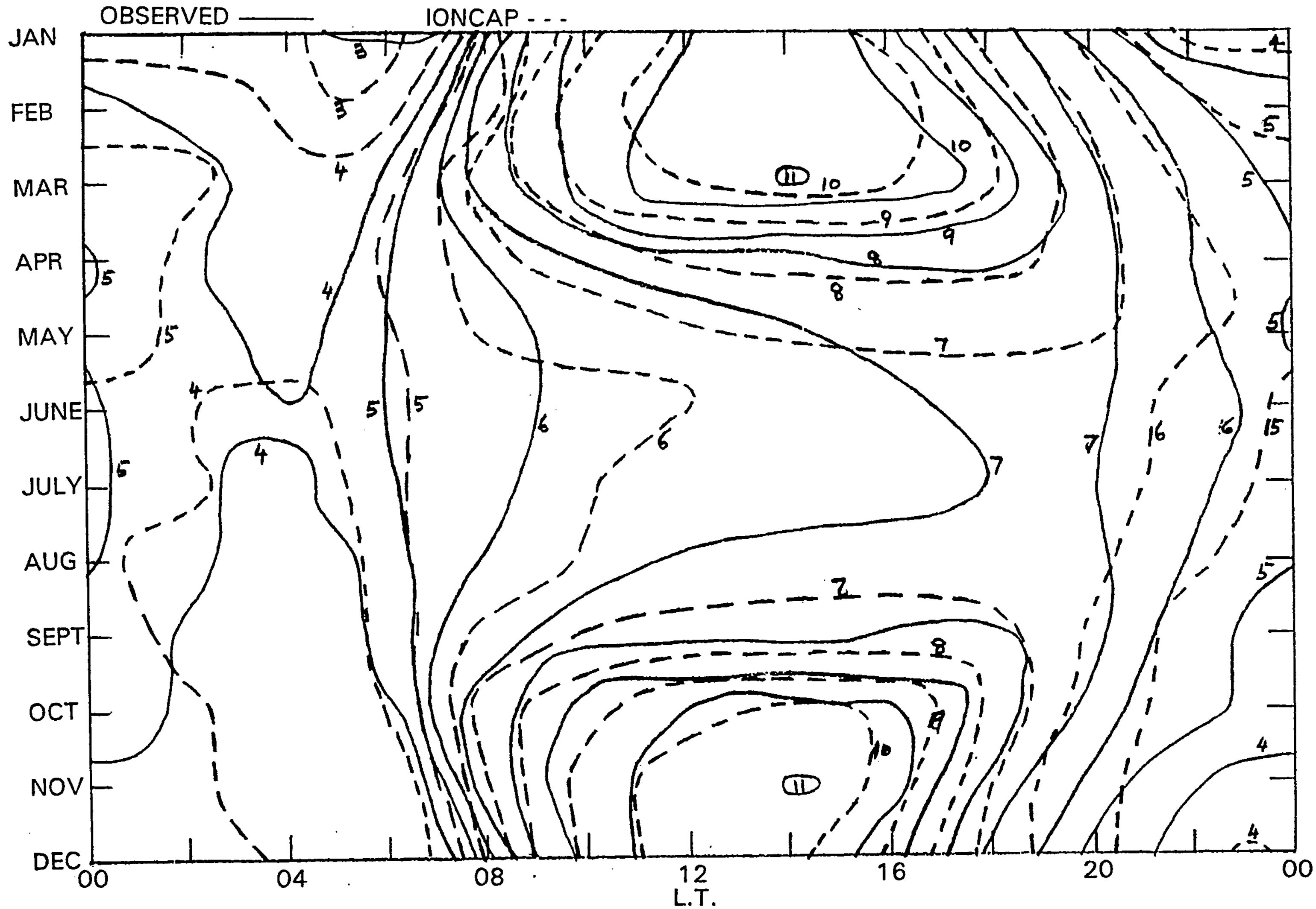

Figure 7B Monthly median contours of f_oF_2 at high solar activity (1969) at Ottawa.

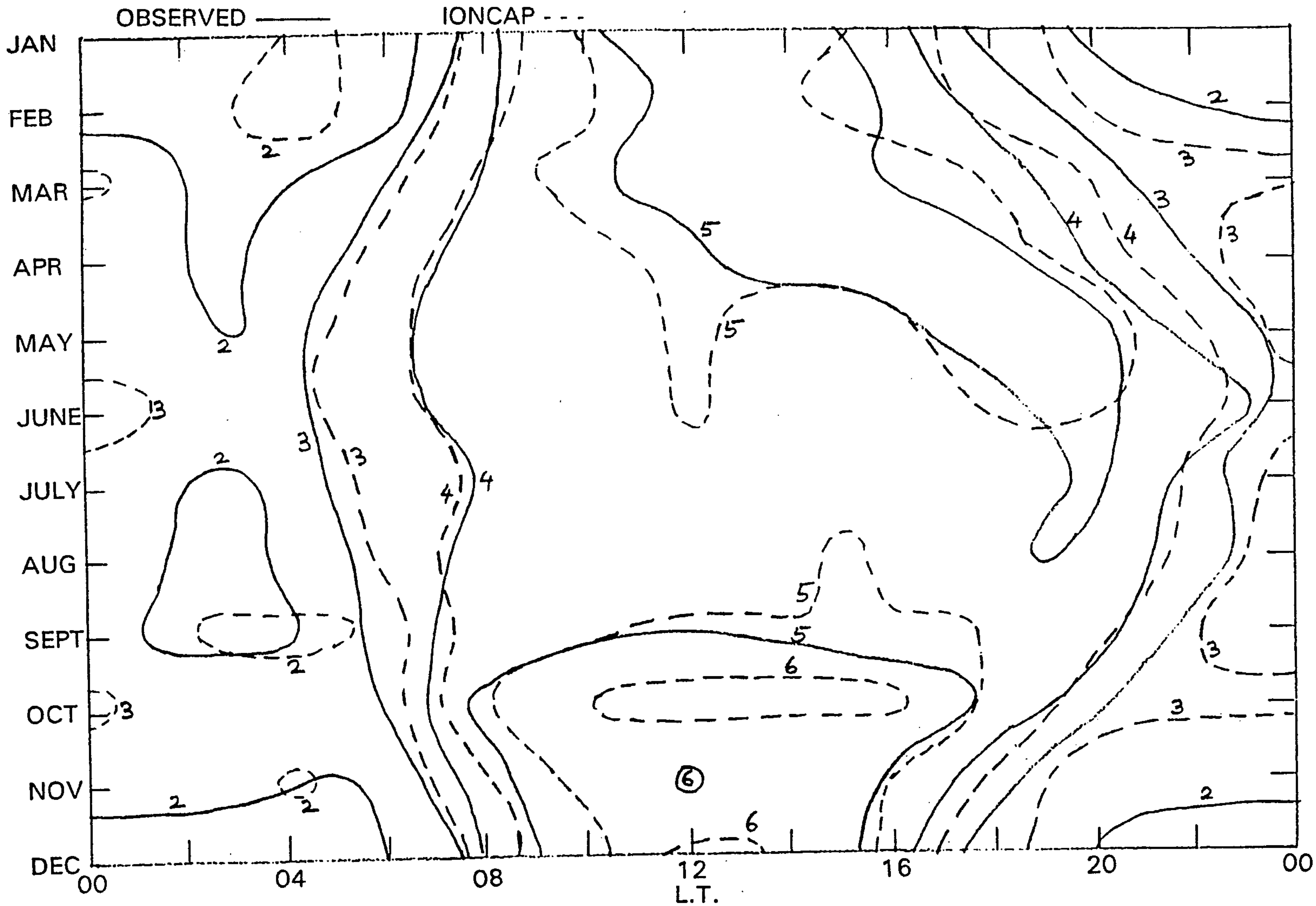

Figure 7C Monthly median contours of f_oF_2 at low solar activity (1976) at St. Johns.

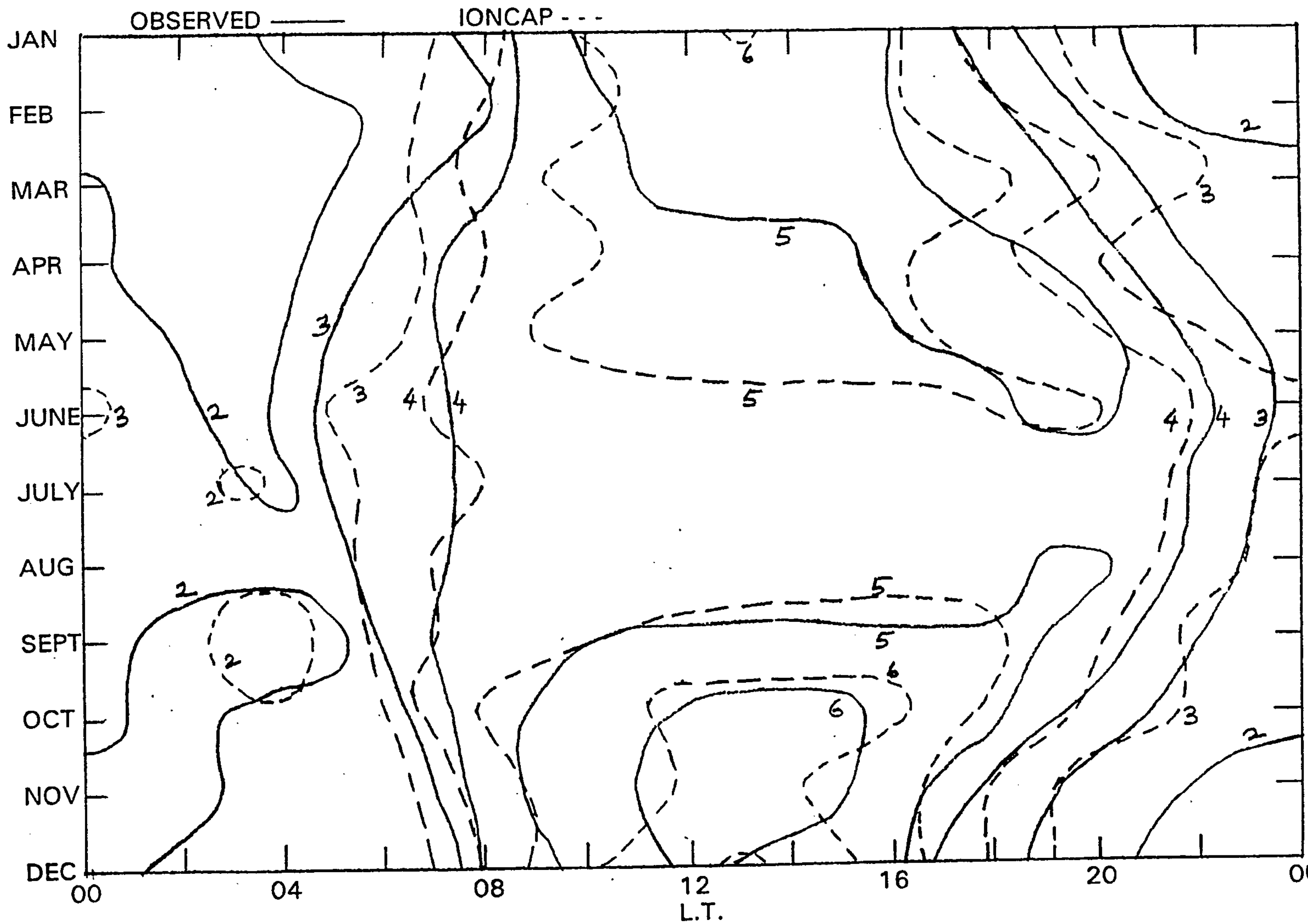

Figure 7D Monthly median contours of f_oF_2 at low solar activity (1976) at Ottawa.

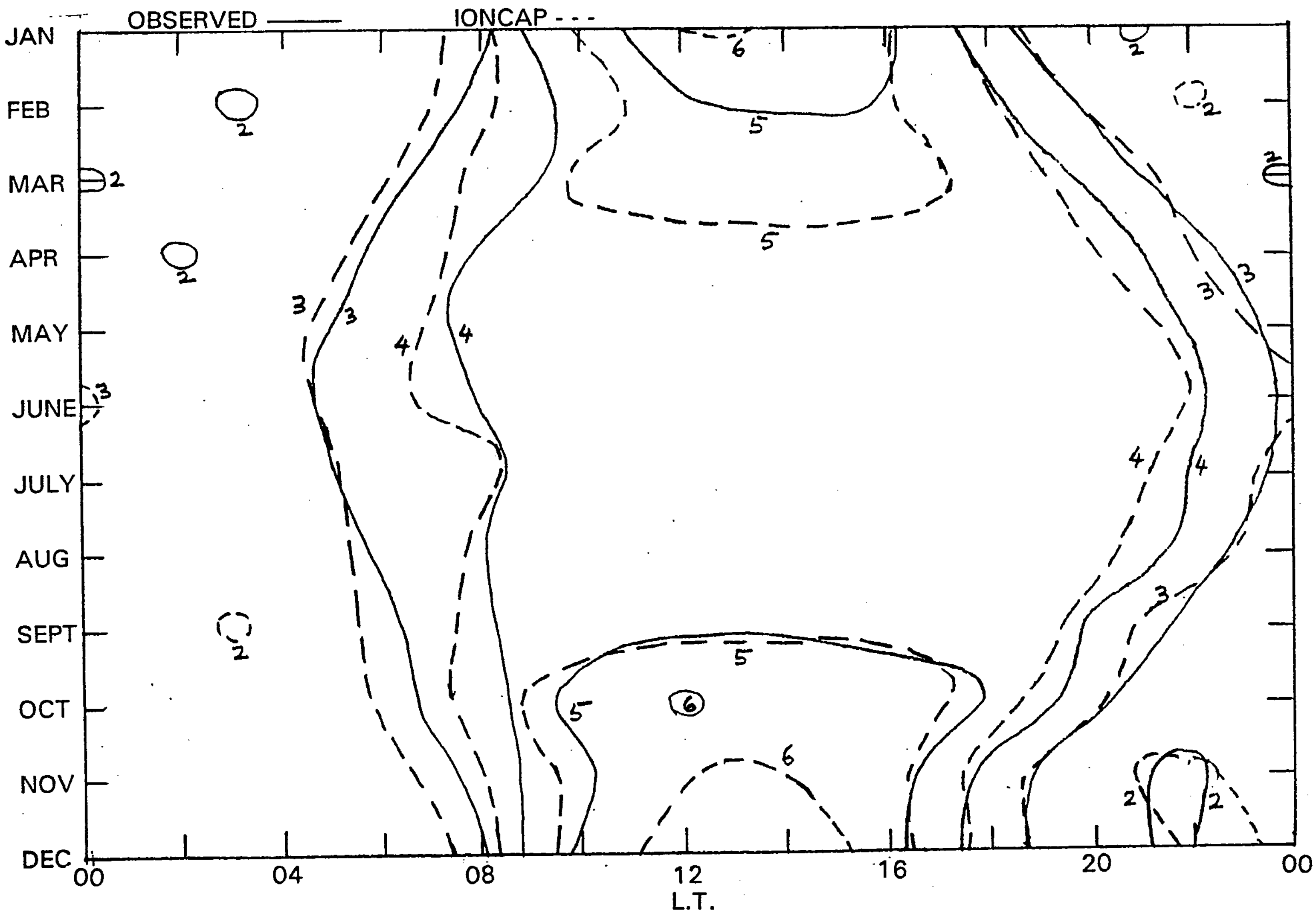

Figure 7E Monthly median contours of f_oF_2 at low solar activity (1976) at Winnipeg.

f_oF_2 values range from 2 to 6 MHz. Again the error is less than 1 MHz. At low solar activity f_oF_2 is observed to be ≤2 MHz in the early morning hours for much longer periods than those predicted by the IONCAP model. As the error at the median level of f_oF_2 is of the order of 1 MHz, the IONCAP program cannot provide a real time prediction with error <0.5 MHz sought by real time data collection systems like the Digital Ionospheric Sounding Systems[5] (DISS) deployed by AWS.

Let us consider the algorithm in Eq. (1) for the short term (next hour) prediction of f_oF_2. In this analysis the error in the prediction of f_oF_2 is computed from

$$\Delta f_oF_2 = | f_oF_{2_{predicted}} - f_oF_{2_{observed}} | \ldots\ldots (5)$$

The percent error (ERR) in the prediction is computed by using

$$ERR(\%) = 100 \frac{\Delta f_oF_2}{foF_{2_{observed}}} \ldots\ldots (6)$$

An improvement (IMPR) in the prediction error is computed by using the error in the prediction of f_oF_2 from the IONCAP program as the reference. It is given by

$$IMPR(\%) = 100 | 1 - \frac{\Delta f_oF_{2_{M_i}}}{\Delta f_oF_{2_{IONCAP}}} | \ldots\ldots (7)$$

The f_oF_2 data are analyzed for each hour on a monthly basis. The f_oF_2, the percent error in f_oF_2, and the improvement I(percent) are computed from Eqs. (5)-(7) for each of the six prediction methods listed in the algorithm section. From these, an average value for the respective error is obtained for the given hour of each month. These values are averaged over all hours to obtain a monthly average error. Also, the values for a given hour are averaged over the year to obtain an hourly average error for the year. All these values are compared for all the methods listed above to determine the merit of each method.

The hourly f_oF_2 data for the stations listed in Table 1 are treated in three categories. The first category is to use all available data. The second category is based on the observation accuracy of the real time data collection systems such as the Automatic Real Time Ionospheric True (ARTIST) height profiles (Reinisch et al[5] 1983) providing electron density distribution and the layer parameters. These systems provide on-line f_oF_2 analysis with an accuracy/error <0.5 MHz for f_oF_2. Therefore for the second category the criterion for the error $f_oF_2 \geq 0.5$ MHz is used. The third category is based on the aim of the radar operation (see in the following in the section on relevance to the OTH operation). The aim of the OTH radar is to maintain a barrier of a given width at a given distance from the radar at all times. This is achieved through frequency management. For the OTH radar every 6 percent change in f_oF_2 slides the barrier by 250 km. Therefore a (6*3≈) 20 percent change (inability to maintain barrier of 500 km if it slides three times its half width) in the f_oF_2 is used as the error criterion in the this category.

The data available from the stations for the error analysis are summarized in Table 3. In this table the name of the station and the year and the category of f_oF_2 data are listed in the first three columns. The next 24 columns list the number of data points available for each of the three categories specified above. The last column lists the total number of data points available for the year. For each station the first line lists the number of hourly observations available for the station. The second line provides the percent (number of observations available/365) hourly coverage for each hour. The next three lines list the percent amount of data (of line 1) used in the respective categories mentioned on the left hand side of the table. The table shows that the data collection rate was high, at about 90 percent, during the high solar activity year (1969) and dropped down to 68 percent during the low solar activity year (1976) at all three stations. The averaging scheme of the algorithm in Eq. (1) starts on the fifth day (n=4) for computing errors in f_oF_2 by various methods. This leads to a reduction of 13 percent of the useful data collected at the stations. Thus ideally in Table 3 the third line should be 87 percent of the first line. The reduced number of predictions : 75 percent during high solar activity period and 63 percent during low solar activity period(<87 percent) is due to discontinuities (gaps) in the data. The next line presents the percent data that resulted in prediction errors in $f_oF_2 \geq 0.5$ MHz, from at least one of the six methods with respect to that from the IONCAP. The table shows that at high solar activity, errors in $f_oF_2 \geq 0.5$ MHz occur for the IONCAP predictions for 67 percent of the time. This occurrence drops to about 45 percent at low solar activity.

Table 3. Number of Observations Available for the Hour

STATION	YR	f_oF_2 PERCENT	U.T. 00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	TOT
ST. JOHNS	69	AVAIL	299	322	336	314	324	322	321	327	325	324	324	323	316	330	327	326	327	337	333	323	319	310	317	302	7728
		%	82	88	92	86	89	88	88	90	89	89	89	88	87	90	90	89	90	91	91	88	87	85	87	83	88
		ALL	75	72	78	74	79	75	74	76	73	76	73	76	77	73	75	77	75	76	77	78	73	72	74	74	75
		>.5MHZ	70	66	75	75	76	69	64	70	66	74	69	71	69	65	69	68	70	72	64	74	69	69	69	69	68
		e>20%	43	49	56	57	53	50	43	41	30	30	23	17	17	13	12	13	13	16	22	30	28	29	34	43	32
OTTAWA	69	AVAIL	332	322	331	324	328	311	316	316	322	333	322	328	331	339	339	336	338	346	343	341	350	342	336	330	7956
		%	91	88	91	89	90	85	87	87	88	91	88	90	91	93	93	92	93	95	94	93	96	94	92	90	91
		ALL	77	78	77	78	78	76	76	77	77	75	76	77	76	74	76	74	78	75	79	79	79	76	76	79	77
		>.5MHZ	68	68	71	72	69	62	65	59	67	66	70	74	73	70	67	68	20	68	68	72	74	71	71	69	60
		e>20%	35	39	47	49	46	42	40	28	28	16	18	19	18	13	12	13	12	11	13	16	19	27	30	31	26
ST. JOHNS	76	AVAIL	170	169	162	145	137	134	177	221	286	297	294	273	268	272	286	297	316	318	309	303	275	248	215	200	5772
		%	46	46	44	40	37	37	48	60	78	81	80	75	73	74	78	81	86	87	84	83	75	68	59	55	66
		ALL	60	54	55	56	48	49	46	50	54	74	72	76	76	69	69	69	68	76	75	75	74	71	71	68	65
		>.5MHZ	45	38	37	37	31	16	33	34	41	58	52	59	55	54	47	49	51	56	61	66	64	62	60	53	48
		e>20%	32	31	33	38	32	18	21	16	16	22	16	19	15	14	12	13	17	19	27	36	36	44	48	46	26
OTTAWA	76	AVAIL	219	196	189	158	135	146	183	209	279	285	292	285	289	293	286	296	295	284	297	295	285	293	282	246	6017
		%	60	54	52	43	37	40	50	57	76	78	80	78	79	80	78	81	81	78	81	81	78	80	77	67	68
		ALL	67	62	58	54	53	39	46	57	56	66	73	72	69	73	72	61	64	72	73	75	72	75	71	71	65
		>.5MHZ	51	43	41	32	31	21	22	37	40	46	52	49	48	49	49	49	44	47	50	67	52	62	59	60	46
		e>20%	43	41	44	39	36	25	21	21	19	16	13	14	10	10	12	9	7	11	15	23	27	38	40	46	23
WINNIPEG	76	AVAIL	205	181	171	146	126	126	139	171	237	299	308	317	318	322	320	323	329	313	323	314	303	278	245	224	6038
		%	56	49	47	40	34	34	38	47	65	82	84	87	87	88	88	88	90	86	88	86	83	76	67	61	69
		ALL	62	51	50	50	45	44	35	49	49	53	72	73	71	72	71	72	69	73	76	73	73	78	73	68	60
		>.5MHZ	49	40	36	40	39	30	19	16	23	28	45	46	47	54	53	47	47	43	46	47	49	59	59	50	42
		e>20%	41	36	38	42	37	30	14	6	3	6	9	10	9	12	13	11	7	7	12	16	25	38	42	41	21

The last line of each group shows that large relative errors (≥20 percent) in f_oF_2 predictions are least frequent (15 percent) in the afternoon. Their occurrence rate increases to 50 percent around the post midnight and early morning hours.

During the low solar activity period of 1976 the data collection at the stations dropped to 35 percent during the early morning hours. This is also seen in Figures 4C-E where the dotted line segments indicate missing data. These periods form a poor sample for the analysis of prediction errors in f_oF_2.

The analysis showed that the modified slope method (Figure 1) provides a slightly greater improvement (Eq. (7)) over the averaged slope method (algorithm in Eq. (1) without the slope correction term in the square bracket), when the converging trend is used for both 04-16 LT and for 16-04 LT by using the opposite signs for respective intervals for f_oF_2 predictions from the full algorithm of Eq. (1). The results for these two time intervals are presented in Table 4. In this table the first three columns list the name of the station, the year, and the category of the data selection. The rest of the table is divided into two sections. In each of these sections, there are 12 columns, one for each month, followed by the column presenting the average value for the year. The aggregate improvement of the respective modified slope method (using the corresponding data segments) is listed in the table. The division in time intervals is not perfect, but on the whole there is a consistent improvement of 3 percent over the averaged slope method. In Figures 4A-E, the change from the modified negative slope to the positive slope corresponds to the peak in the diurnal variation of f_oF_2. A look at Figure 1 shows that the second order correction using a consistent converging trend for all 24 hours results in improved predictions of f_oF_2.

The average error (Eqs. (5) and (6)) in the prediction of f_oF_2 for each year is computed over the two proposed intervals. The results are presented in Table 5. The first three columns on the left hand side list the station, the year, and the category for the analysis. The table is divided into two sections along the columns for the two time intervals specified above. In each section the errors are listed for the six prediction methods. The number of data points and their percent contribution to the respective time intervals are also listed. The table shows that the errors are largest for the IONCAP method and reduce successively for the other methods: observed median (which is the accurate IONCAP prediction), prior four days' average f_oF_2, average slope method, and the modified slope method. Note that for one time interval the positive slope method is better and for the other

Table 4. Improvement (percent) by the Modified Slope Method Over the Averaged Slope Method

Percent Gain Over Average Slope Method

			04-15 LT (NEGATIVE SLOPE) MONTH													16-03 LT (POSITIVE SLOPE) MONTH												
STATION	YR	FOF2	01	02	03	04	05	06	07	08	09	10	11	12	AVG	01	02	03	04	05	06	07	08	09	10	11	12	AVG
ST.JOHNS	69	ALL	1	0	-1	-1	2	1	0	1	0	1	0	2	1	3	1	2	2	0	-1	1	1	1	2	2	3	1
		>.5MHZ	1	0	-1	-1	2	1	0	1	0	1	0	2	1	3	1	2	2	0	-1	2	1	0	2	2	3	1
		e>20%	6	-2	-2	-2	2	1	1	1	-1	2	0	8	1	4	2	2	2	1	-1	3	1	1	3	3	3	2
OTTAWA	69	ALL	0	0	0	0	1	1	0	0	0	2	1	2	1	4	3	1	2	1	1	2	1	2	1	2	3	2
		>.5MHZ	1	0	0	0	1	0	-1	0	0	2	1	2	1	3	2	0	2	1	1	2	1	1	1	1	2	1
		e>20%	3	0	0	1	1	0	-1	-1	-1	2	1	5	1	7	3	1	3	3	1	4	2	2	1	1	2	3
ST.JOHNS	76	ALL	1	-3	4	2	1	6	2	4	2	0	-1	6	2	4	5	-1	2	4	3	4	3	3	1	7	6	3
		>.5MHZ	2	-4	5	2	1	7	1	6	2	0	-1	7	2	4	5	0	2	4	3	5	3	3	1	9	7	4
		e>20%	1	-5	6	3	1	5	6	6	3	-1	-1	8	3	6	6	-1	3	5	6	6	4	3	1	9	6	5
OTTAWA	76	ALL	5	2	1	2	2	1	2	2	5	-1	4	4	2	3	12	2	2	3	4	0	2	5	2	5	4	4
		>.5MHZ	6	2	1	2	2	3	1	4	5	-1	5	4	3	4	13	2	2	3	5	0	4	4	2	6	4	4
		e>20%	8	2	1	2	3	9	2	8	6	-1	5	4	4	4	13	2	3	3	5	6	1	4	7	2	5	5
WINNIPEG	76	ALL	2	-1	-2	2	2	4	3	-1	3	-1	2	2	1	2	4	6	3	2	0	0	0	3	3	2	8	3
		>.5MHZ	2	-1	-7	2	5	6	3	0	3	-1	2	3	1	2	5	6	4	3	1	-1	3	3	4	2	12	4
		e>20%	0	1	-5	11	12	6	6	3	2	-2	1	3	3	2	6	7	5	4	3	-1	4	5	8	5	12	5
GRAND AVG			3	-1	0	2	3	3	2	2	2	0	1	4	2	4	5	2	3	2	2	2	2	3	3	4	5	3

Table 5. Error in the Prediction of fof2 for Various Schemes

ERROR IN f_oF_2

TIME INTERVAL			NO OF OBSERVATIONS				04-15 LT METHOD								16-03 LT METHOD							
									1	2	3	4	5	6			1	2	3	4	5	6
STATION	YR	f_oF_2	AVAIL	%	TOT	%	USED	%							USED	%						
ST. JOHNS	69	ALL	6576	75	5819	88	2922	50	.89	.76	.68	.38	.40	.38	2897	50	.93	.81	.77	.50	.49	.52
		>.5MHZ	5400	82	2669	49			.92	.79	.71	.39	.41	.39	2731	51	.96	.83	.80	.51	.50	.54
		e>20%	2430	37	965	40			18	16	15	7	7	7	1465	60	26	23	22	12	12	13
OTTAWA	69	ALL	6804	78	6123	90	3002	49	.79	.73	.64	.34	.35	.35	3121	51	.84	.70	.66	.35	.34	.37
		>.5MHZ	5478	81	2659	49			.83	.77	.68	.35	.36	.35	2819	51	.88	.73	.70	.36	.35	.38
		e>20%	2042	30	837	41			17	16	14	7	6	6	1205	59	22	20	18	8	8	9
ST. JOHNS	76	ALL	4620	53	3849	83	2050	53	.49	.42	.41	.32	.33	.31	1799	47	.57	.46	.46	.36	.34	.38
		>.5MHZ	2928	76	1498	51			.53	.47	.46	.36	.37	.35	1430	49	.61	.50	.50	.38	.36	.41
		e>20%	1424	31	511	36			15	13	12	9	0	9	913	64	26	18	18	13	12	14
OTTAWA	76	ALL	4865	55	4018	83	2039	51	.46	.40	.38	.27	.28	.26	1979	49	.51	.42	.42	.29	.28	.31
		>.5MHZ	2836	58	1379	49			.50	.44	.42	.30	.31	.29	1457	51	.56	.47	.47	.32	.30	.33
		e>20%	1360	28	437	32			15	13	13	8	8	8	923	68	22	17	17	12	11	12
WINNIPEG	76	ALL	4886	56	3970	81	2060	52	.46	.40	.37	.25	.27	.24	1910	48	.48	.46	.46	.37	.35	.38
		>.5MHZ	2666	55	1324	50			.50	.45	.41	.27	.29	.26	1342	50	.52	.50	.51	.40	.39	.42
		e>20%	1128	28	319	28			16	13	11	8	8	7	809	71	18	18	17	15	14	16

Methods; 1) Ioncap, 2) Observed Median/ Accurate Ioncap, 3) Prior Four Days' Average, 4) Average Slope, 5) 2nd order correction with Negative Sign, and 6) 2nd Order Correction with Positive Sign.

interval the negative slope method is better, (essentially the improvement is associated with the converging trend approach). The significant result is that the error of 0.9 MHz from the IONCAP during high solar activity is reduced to 0.4 MHz by the use of the proposed scheme. At low solar activity the respective reduction is from 0.5 MHz to 0.3 MHz. Thus the proposed method reduces the error to 50 percent of that from the IONCAP method. Considering the magnitude of errors (in MHz), significant improvement is observed at both high as well as low solar activity periods.

In terms of percent error, (≥20 percent) the large relative errors occur more frequently (65 percent of the time) in the 16-04 LT interval than (35 percent) in the 04-16 LT interval.

The percent improvement (Eq. (7)) averaged over the whole year is presented in Table 6, which has the same format as Table 5. The errors are averaged separately for the high and low solar activity periods. The improvement is better at high solar activity (52 percent) than at low solar activity (35 percent). Note that the improvements by the observed median (that is, accurate IONCAP) and by 'prior four days' average' methods are small: 10 percent and 14 percent respectively. Thus a prediction from a) the IONCAP, b) an accurate IONCAP and c) from the averaging method (similar to that proposed by Rush and Gibbs[3] (1973)) are unable to provide the reasonably accurate prediction of f_oF_2 needed for the real time application. The division of the algorithm into two time intervals is slightly better than the use of the averaged slope method for improving the real time predictions of f_oF_2.

The averaged monthly values for the improvement using the modified slope method for the three categories for the stations are presented in Table 7. The table shows similar improvements for each month in all the categories, showing the improvement in the predictions based on the algorithm in Eq. (1). The improvements in f_oF_2 predictions are larger (52 percent) at high solar activity and a little lower (33 percent) at low solar activity. Ottawa and Winnipeg stations show smaller improvements (<25 percent) in the months of June, July, November and December during the period of low solar activity.

The percent improvement is averaged for each LT hour of the year to check if the improvement of the f_oF_2 prediction from the algorithm has any time dependency. The results are summarized in Table 8. Figures 5A-E show that the transition periods of large slopes cover the

Table 6. The Improvement (percent) in the Prediction of f_oF_2 By Various Schemes Compared to That from IONCAP

Percent Improvement

			04-15 LT					16-03 LT				
			METHODS					METHODS				
STATION	YR	f_oF_2	2	3	4	5	6	2	3	4	5	6
ST.JOHNS	69	ALL	12	21	53	52	54	12	16	44	46	42
		>.5MHZ	12	21	54	52	55	12	15	45	46	42
		e>20%	4	11	55	54	55	3	10	44	46	41
OTTAWA	69	ALL	9	18	54	52	54	17	19	56	58	54
		>.5MHZ	9	18	55	53	55	16	19	57	59	55
		e>20%	0	9	56	56	57	10	17	57	59	54
	69	AVG	8	16	55	53	55	12	16	51	52	48
ST.JOHNS	76	ALL	11	11	27	25	29	17	14	32	35	28
		>.5MHZ	10	11	26	24	29	16	12	31	35	27
		e>20%	8	10	28	27	31	20	16	34	38	30
OTTAWA	76	ALL	13	15	36	35	38	17	16	39	42	36
		>.5MHZ	11	14	34	33	37	16	14	39	43	37
		e>20%	8	19	36	37	40	16	15	40	44	37
WINNIPEG	76	ALL	12	15	38	32	39	6	4	21	24	18
		>.5MHZ	9	14	38	32	39	4	2	18	21	14
		e>20%	9	18	40	37	43	-1	1	12	17	9
	76	AVG	10	14	34	31	36	12	10	30	23	26
GRAND AVG			9	15	44	42	46	12	13	40	43	37

Methods: 1) Ioncap, 2) Observed Median/ Accurate Ioncap, 3) Prior Four Days' Average, 4) Average Slope, 5) 2nd Order Correction with Negative Sign, 6) 2nd Order Correction with Positive Sign.

Table 7. Percent Improvement by Modified Slope Method

			MONTH												
STATION	YR	f_oF_2	01	02	03	04	05	06	07	08	09	10	11	12	AVG
ST.JOHNS	69	ALL	39	51	52	56	52	44	42	48	64	50	42	49	
		>.5MHZ	39	52	52	56	52	44	44	51	64	51	43	49	
		e>20%	29	61	59	63	61	33	42	43	63	43	47	44	
OTTAWA	69	ALL	35	53	56	59	54	64	59	65	65	63	50	40	
		>.5MHZ	35	53	56	60	56	64	60	66	65	64	50	41	
		e>20%	24	63	60	64	58	63	60	66	65	70	48	31	
	69	AVG	34	56	56	60	56	52	51	57	64	57	47	42	52
ST.JOHNS	76	ALL	27	29	38	41	33	12	26	25	39	47	21	17	
		>.5MHZ	25	28	38	42	35	11	26	25	39	48	18	12	
		e>20%	25	27	46	42	38	13	21	28	42	55	13	19	
OTTAWA	76	ALL	28	27	58	51	41	28	26	29	40	46	30	42	
		>.5MHZ	26	28	58	54	42	26	24	21	42	48	28	43	
		e>20%	33	31	61	61	51	18	10	24	43	54	24	49	
WINNIPEG	76	ALL	29	42	43	34	33	27	18	29	32	43	30	14	
		>.5MHZ	29	44	46	31	32	28	17	30	32	45	29	4	
		e>20%	31	48	52	28	33	26	10	19	32	45	30	13	
	76	AVG	28	34	49	43	38	21	20	26	38	48	25	24	33
GRAND AVG			31	45	52	51	47	37	36	41	51	52	36	33	43

Table 8. Annual Improvement for Each Hour (Averaged for 12 Months)

		LOCAL TIME																								
STATION YR	f_oF_2	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	AVG
ST.JOHNS 69	ALL	45	63	63	59	54	59	52	51	53	55	54	46	53	58	61	62	57	45	36	29	36	33	34	46	50
	>.5MHZ	46	63	63	60	55	50	53	51	53	55	54	47	53	68	62	63	58	46	36	30	37	32	34	46	51
	e>20%	48	69	68	64	58	48	54	45	46	56	52	53	45	66	69	69	57	30	32	29	36	31	37	49	50
OTTAWA 69	ALL	57	64	63	57	56	50	49	52	47	48	53	52	59	62	62	61	58	57	53	49	52	57	64	63	56
	>.5MHZ	58	65	63	58	58	51	51	53	48	49	53	53	60	63	62	62	59	62	54	48	53	57	64	65	57
	e>20%	61	70	66	63	60	50	50	49	48	53	51	50	69	64	70	70	57	58	51	26	59	62	67	68	58
69	AVG	53	66	64	60	57	51	52	50	49	53	53	50	57	64	64	65	58	50	44	35	46	45	50	55	54
ST.JOHNS 76	ALL	41	37	40	22	9	17	29	32	42	35	34	24	34	32	28	36	33	34	40	25	31	45	29	45	32
	>.5MHZ	44	38	45	17	5	11	28	31	44	37	33	21	33	35	29	34	33	35	40	25	30	42	28	44	32
	e>20%	49	46	49	25	5	8	17	28	49	43	34	32	46	39	32	38	34	36	38	23	27	51	34	51	35
OTTAWA 76	ALL	43	43	30	39	33	31	33	39	34	47	40	41	36	40	39	45	47	46	39	39	42	53	48	36	40
	>.5HMZ	44	43	27	34	34	21	33	38	32	49	39	44	35	37	39	46	50	49	40	40	41	53	50	38	40
	e>20%	45	48	32	37	33	24	35	40	39	56	38	48	41	33	44	56	58	49	37	42	36	55	50	3	42
WINNIPEG76	ALL	2	4	21	19	14	23	30	40	46	51	51	50	53	53	55	50	47	38	28	26	23	33	23	16	31
	>.5MHZ	-7	5	18	14	6	-32	26	39	47	55	54	54	54	56	61	53	51	39	28	25	27	17	18	15	30
	e>20%	-18	10	24	7	8	-18	33	35	53	59	57	59	54	62	65	51	45	26	18	20	27	22	16	5	30
76	AVG	27	30	32	24	16	4	29	36	43	48	42	41	43	43	44	45	44	39	34	29	32	41	33	32	35
GRAND AVG		40	48	48	42	37	28	40	43	46	50	48	46	50	53	54	55	51	44	39	32	39	43	41	44	45

periods 04-09 LT and 16-23 LT. For high solar activity (year 1969) the improvement in f_oF_2 predictions is good for all the LT hours. At low solar activity the improvement in f_oF_2 prediction is low (<25 percent). A factor for such poor performance would be the large spread in f_oF_2 at the given hour seen in Figures 6 A-E.

The number of occurrences of poor performance (improvement <25 percent) for f_oF_2 predictions from the algorithm were counted for the hourly values of the improvement (Eq. (7)). At high solar activity the algorithm performs poorly for 10 percent of the time, with the occurrence more frequent (2:1) in the 16-04 LT interval than in the 04-16 LT interval. At low solar activity (1976) the poor performance occurs for 25 percent of the time intervals. Poor performance occurred more frequently in the months of December to February and June to August.

An additional approach of an occurrence frequency method is used for determining the performance of each method. For each observation the methods are ranked in descending order with an increase in prediction error. When the errors are equal the respective methods are ranked equal. The cumulative count of the respective methods is used for determining the performance of these methods. Also, the frequency is counted for each method only when the method is the best (produces the least error among these methods) and also for the case when the method is the worst (produces the largest error). The results for the best and the worst method approach (discussed above) are shown in Figure 8. The counts of the modified slope method over the respective time intervals are combined. The relative count for performance for the respective methods show that the IONCAP, the observed median and the prior n days' average methods are worse (short dotted lines) than the averaged slope and the modified slope methods. The best predictions are more frequent from the modified slope and the averaged slope methods than from the remaining methods (long dotted lines). The overall performance (continuous line) of the slope methods is better than that from the remaining methods. Considering all the three groups: general, best, and worst performance, the modified slope method with two time intervals combined, 04-16 for positive slope and 16-04 for negative slope, is the best method for obtaining f_oF_2 predictions from the algorithm in Eq. (1). The IONCAP and the observed median (which is not available in reality) methods are unable to provide the f_oF_2 predictions that will satisfy the needs of the real time operating systems.

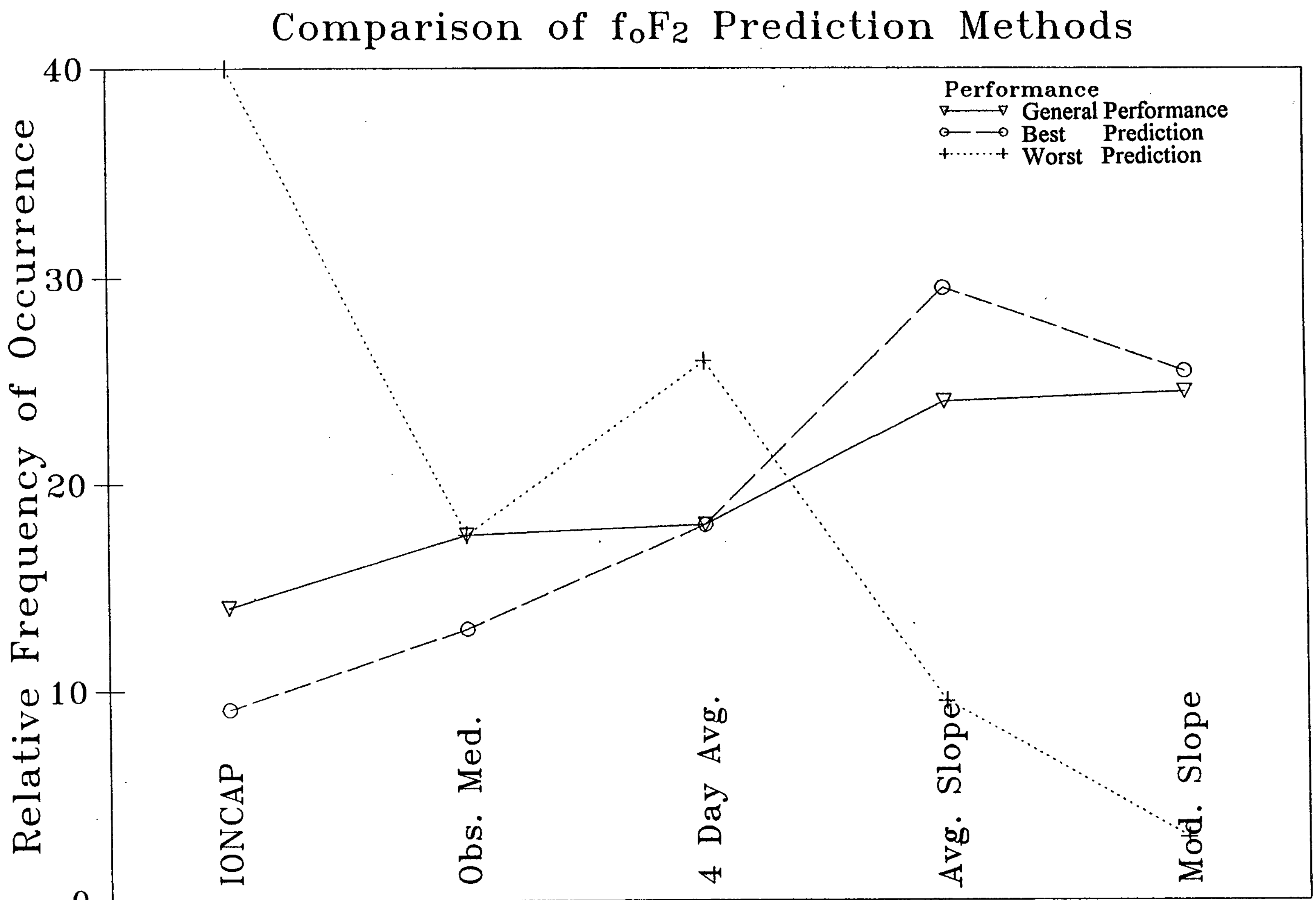

Figure 8. Performance of the schemes used for the f_oF_2 predictions.

4. CONCLUSION

The algorithm from Eq. (1) proposed for improving the short term real time f_oF_2 prediction is better than the other methods like the IONCAP and the 'prior n days' averaged f_oF_2. Depending on the circumstances one may truncate the algorithm at various terms on the RHS of Eq. (1). The best results are obtained by dividing the 24 hour period into two intervals and using the slope correction with the appropriate sign for each interval to assure the use of the converging trend shown in Figure 1. The errors in the f_oF_2 predictions are reduced from 0.9 MHz for the IONCAP to 0.4 MHz at high solar activity (1969) and from 0.5 MHz to 0.3 MHz at low solar activity (1976). Thus the proposed algorithm improves the f_oF_2 predictions by 50 percent at high solar activity and by 40 percent at low solar activity. The proposed method, though not perfect, provides a minimum improvement of 25 percent in predicting f_oF_2 for 80 percent of the time. Also, (Figure 8) this method has better overall performance, and is the least often the worst prediction method.

Among the various schemes considered here, the IONCAP is unable to provide a reasonable f_oF_2 prediction for real time operational systems. Even if the IONCAP succeeds in reproducing the observed f_oF_2 median values, the corresponding improvement in the f_oF_2 prediction is only 10 percent. Prior 'n days' averaged f_oF_2 improves the prediction by 14 percent over that from the IONCAP method, not a very significant improvement.

5. RELEVANCE TO OTH OPERATION

Dandekar and Buchau[1](1986) have discussed the problem in detail for the sunrise transition period. The 'M' factor is a ratio of the radar operation frequency to f_oF_2 at the midpoint of the radar range. The radar range is also a function of the 'M' factor and varies with other F_2 layer parameters; h_m - peak height, h_0 - base height, and y_m -half width of the layer. Keeping all layer parameters (except f_oF_2) and radar frequency fixed, the radar range increases (/decreases) with increase (/decrease) in f_oF_2. Using the equation relating range to M developed by Appleton and Beynon[6] (1940), Dandekar and Buchau[1] showed that for the radar range 2500-3000 km, a 2.3 percent change in M moves the barrier 100 km. This corresponds to a 6 percent change in M for a sliding of the barrier of 500 km, that is, by half of its width. In Figures 5A-E, changes in f_oF_2 larger than 20 percent are seen during the sunrise and sunset transition periods. Dandekar and Buchau[1] (1986)

observed changes as high as 60 percent in f_oF_2 at Ottawa and Arguello in the winter season in 1969. If the radar operation frequency is to be adjusted when the barrier slides by half of its width, the frequency has to be changed every 12 minutes to cover the f_oF_2 change of 30 percent and every 6 minutes for the change of 60 percent. Because such rapid adjustments of the radar frequency are needed during sunrise/sunset transition periods, improved predictions of f_oF_2 with error reduced by 50 percent is very helpful to the radar operation.

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